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Integrated plant nutrition systems

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Integrated plant nutrition systems

Report of an Expert Consultation

Rome, Italy
13-15 December 1993

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Preface

The increasing pressure on the land of a fast-growing world population has made it necessary to intensify agricultural production. Efficient use of mineral fertilizers has proved to be a quick way of boosting crop yields per unit area of land; however, it must be realized that cost and other constraints frequently deter farmers from using them in adequate quantities and balanced proportions.

Over the last ten years, FAO has been actively engaged in the development of an 'Integrated Plant Nutrition System' (IPNS), an approach through which the management of plant nutrition and soil fertility in farming systems is adapted to site characteristics taking advantage of fertilizers toward production increases but aims at environmental, social and economic viability. Only organic sources and recycling do not suffice to meet increased demands for food on a fixed land area. On the other hand environmental hazards and economic constraints often preclude that crop nutrient requirements be solely met by mineral fertilizers. Hence a judicious combination of mineral fertilizers with organic sources of nutrients is being promoted. These mixed applications are not only complementary but synergistic since organic inputs have beneficial effects beyond their nutritional content.

Organic resources can be produced on the farm but may also come from non-cropped areas, from town refuse, industrial wastes, etc. so that their mobilization may involve an entire community rather than the individual farmer only. The great variety of possible combinations and of nutrient sources require an adaptation at the level of the farm and of the village. The contribution of different sources of nutrients within an applicable package needs to be assessed and farmers need to be trained, organized and encouraged to apply an improved approach to raising productivity while conserving the natural resource base.

Extension staff who are to translate basic data into practical recommendations will need to take stock of both farmers' know-how and research results. Available knowledge will need to be competently summarized and economically tested in order to ensure the adoption of an IPNS approach by farmers.

Wishing to draw from a wide range of experience, FAO organized this consultation with a view to strengthening its plant nutrition management programme and to seeking advice on priorities for its future work.

In addition to the above, it is hoped that various technical papers presented at the consultation and highlights of discussion will be of interest to the scientific community, development agents and policy makers. Therefore, the proceedings of the Expert Consultation and the papers presented are published as an *FAO Fertilizer and Plant Nutrition Bulletin*.

Acknowledgements

This report of the Expert Consultation on Integrated Plant Nutrition Systems is accompanied by the papers presented and discussed at the Consultation. As the sponsoring organization, FAO expresses its great appreciation to the participants for their support and their contributions to the deliberations. Their willingness to prepare the basic material for the discussions is gratefully acknowledged.

Thanks are also due to the staff of the various departments and units of FAO who took part in the Consultation: Agriculture, Forestry, Economic and Social Policy, Development, FAO/IAEA Joint Division and the Regional Office for Asia and the Pacific. Special mention is due to the team of the Plant Nutrition Management Service that organized and ran the Consultation: Mr. A.L. Angé, Chief, Dr. R.N. Roy, Senior Officer, IPNS Group, and Mr. W. Burgos, Technical Officer, IPNS Group.

The untiring efforts of Ms. C.D. Smith Redfern in typing, formatting and proof-reading the Proceedings are thankfully acknowledged.

Contents

SUMMARY REPORT, CONCLUSIONS AND RECOMMENDATIONS

SUMMARY REPORT

Over the last ten years FAO has been actively supporting the development of an Integrated Plant Nutrition System (IPNS), an approach through which the management of plant nutrition and soil fertility in cropping and farming systems is adapted to site characteristics and to locally-available resources. IPNS ensures that plant nutrition be environmentally, socially and economically viable. Concurrently it encourages, informs, trains and organizes farmers to increase crop production while sustaining soil productivity.

Though the efficient use of mineral fertilizers is recognized to be a quick and sure way of boosting crop production it must be realized that their cost and other constraints frequently deter farmers from using them in recommended quantities and in balanced proportions. Hence a judicious combination of mineral fertilizers with locally-available organic sources of plant nutrients is being promoted. These mixed applications are not only complementary but synergistic since organic inputs have beneficial effects beyond their nutritional components. The great variety of possible combinations and of sources of organic materials, however, require an adaptation at the level of the farming system and of the village.

FAO, wishing to draw from a wide range of expertise, organized this Consultation with a view to strengthening its IPNS programme and to set priorities for future work.

The Expert Consultation was organized along six major themes:

- Importance of plant nutrition for meeting the agricultural product requirements.
- Soil organic matter, biomass, soil micro-flora and management of integrated plant nutrition systems.
- Renewable supply of plant nutrients from natural sources and plant nutrient transfer to crops.
- Place and role of local and external sources of plant nutrients in cropping systems and their evaluation.
- Plant nutrient management in farming systems and in watersheds and territories.
- Priorities for FAO's IPNS programme.

Importance of plant nutrition for meeting the agricultural product requirements

This theme was introduced with an overview of fertilizer use and nutrient balances in various continents or sub-continents. As a result of economic and environmental considerations, fertilizer use had decreased in recent years in North America and in Europe. In South Asia and in China fertilizer use had markedly increased as a result of an urgent need for intensification of agriculture on existing arable land. On the contrary, in Africa, fertilizer use was below minimum needs to the extent of serious nutrient depletion in many countries of the continent. A steadily decreasing arable land *per caput* ratio will require an intensification of agricultural practices including improved plant nutrition. An IPNS approach should be promoted in order to make best possible use of locally-available organic sources and in order to enhance the efficiency of the mineral fertilizers that are being applied. It was pointed out that increasing needs of agricultural production could not be met either by 'low-input' schemes or by 'organic-farming-only', especially in soils of inherently low fertility which prevail in the humid tropics.

It was stressed that due attention should be given to the interaction of plant nutrition with other production factors such as water management, weed and disease control, efficient tillage and other crop management practices. Considering the site-specificity of these interactions, IPNS should be geared toward the actual conditions at the level of the field, the farm, the village or the watershed. It should aim at ensuring sustainable agricultural and rural development with special attention to developing environmentally-sound plant nutrition technologies.

The implementation of the IPNS approach should be the responsibility of scientists, advisers, and mainly of the farmers themselves. Scientists should critically test results of research and existing information before recommendations are made for practical application. Advisers should translate the basic knowledge into practical technologies taking into account farmers' know-how and experience. Farmers should combine production with the enhancement of soil fertility, it being understood that they are given the economic motivation to do so.

Soil organic matter, biomass, soil microflora and management of integrated plant nutrition systems

This theme was devoted to a review of the sources of nutrients which, in an IPNS approach, could be derived from organic sources.

During the last three decades food production increased remarkably due to the introduction of high-yielding varieties of rice, wheat and maize combined with mineral fertilizers as a major input. Stagnating yields indicate, however, that a combination of mineral fertilizers with organic sources of plant nutrients will need to be encouraged.

It was stressed that the beneficial effects of organic matter go beyond the supply of nutrients - which in many instances was relatively small - by the enhancement of soil structure, water storage, cation exchange capacity and biological activity. It was recognized, however, that although these benefits were real they had not often been quantified and that additional research was needed to appraise the actual effects on production and environmental protection.

It was generally found that the application of organic materials was more beneficial in the form of manure or compost than in the form of mulches. The latter practice is especially relevant to reduce erosion and conserve moisture but is less effective in providing nutrients. It was found that the soil biomass was a better measure to assess the reserves of potentially available nutrients than the classical chemical analyses of soil organic matter.

The techniques of processing organic materials, especially of organic wastes, were found to be important in terms of improving their quality as sources of nutrients and soil conditioners. Humification parameters and electrophoretic procedures can be used to establish quality criteria of soil organic matter and to follow the stabilization and turnover rate of organic amendments.

With the discussion on nutrient cycling and supply in agroforestry systems it was observed that the adoption rate of alley-cropping by farmers was very low, possibly because of the high labour requirements versus the relatively small amount of nutrients taken up by the crop from tree prunings. Agroforestry systems have been shown to reduce leaching losses of plant nutrients. However, the 'pumping up' of nutrients was conditioned by soils having no physical or chemical barriers to root penetration and having large reserves of weatherable minerals. These conditions were not frequently met in the humid tropics and thus agroforestry techniques would need to be additionally validated prior to their further extension.

It was found that a judicious organization of fallow did contribute to enhanced nutrient availability and soil improvement. A clear distinction needed to be made between different types of fallow, under different agro-ecological conditions, in terms of which fallow management should be determined. The control of soil organic matter needs to be tailored to local physical and socio-economic conditions through a participatory and multidisciplinary approach.

When evaluating the potential contribution of organic sources of nutrients to crop growth it was concluded that organic matter management is an important component of an integrated plant nutrition system. However, responses differ greatly depending on environmental conditions, sources of organic matter, and form of application. There is a need for adequate methods to evaluate organic materials for their value as nutrient sources and for assessing their other effects on soil improvement and crop production. Predictive models to evaluate the value of organic inputs should increasingly be based on studies of processes rather than on dispersed trials.

The control of the soil organic matter balance, rather than the control of soil organic matter losses, is critical to an integrated plant nutrition system. It is of vital importance therefore to promote technologies which, in addition to crop production, also aim at a favourable soil organic matter balance and the prevention of erosion. The design of such technologies should bear on a sound agro-ecological approach and be integrated in improved land husbandry and introduced into current farmers' priorities.

Renewable supply of plant nutrients from natural sources and plant nutrient transfer to the crops

A major source of a renewable supply of nitrogen is biological nitrogen fixation. The Consultation acknowledged that nitrogen-fixing systems, including free living symbiotic or associative organisms, contribute significant amounts of fixed nitrogen to soil-crop systems. Rhizobia-legume systems fix nitrogen at rates in the range of 50-300 kg N/ha/year. Cyanobacteria fix 15-25 kg N/ha/year and azospirillum-grass associations 10-30 kg N/ha/year. It was felt therefore that more attention should be paid by national agricultural research to nitrogen-fixing systems and that laboratories should be established for production of quality inoculants. The inclusion of legume crops in cropping systems or rotations should be encouraged and more use should be made of leguminous green manures and nitrogen-fixing trees. The interaction between mineral fertilizers and nitrogen-fixing systems should be further studied towards a better integration within plant nutrition systems.

With regard to inputs from rain, dust and sedimentation it was felt that the contributions from atmospheric sources may be important in low-input systems, especially with respect to N and S. In high-input systems their contribution may be negligible. There is considerable spatial variability in the inputs, and frequently there will be substantial temporal variation. More information is required on the nutrient quality of the irrigation water. There is a need for a more comprehensive database if these inputs are to be incorporated into nutrient budgets.

The occurrence and weathering of primary forms of phosphorus and potassium in soils and the mechanisms involved in their supply to plants were discussed. Information is available on the rate of weathering of apatite, by far the most abundant primary form of P in soils. In contrast, quantitative information on the rates of weathering of K micas and feldspars in soils is limited. Soil reserves may contribute to meet plant requirements in weakly weathered soils. However, in intensive agricultural systems the supply from soil reserves is insufficient to meet crop requirements. This applies especially to strongly weathered soils in the tropics where mineral reserves are inherently very low or absent.

A study on renewable supplies of plant nutrients in China showed that of a total nutrient use on all crops, about 66 million tons in 1991-92, about 45% were derived from mineral fertilizers and about 55% from organic materials. The total volume of organic material used was about 3 thousand million tons, with an average total nutrient content of about 1.2%. The cost of labour and transportation will limit the use of organic materials in the future. In Eastern China, where these costs are relatively high, the use of organic materials has sharply decreased in the recent past.

Place and role of local and external sources of plant nutrients in cropping systems and their evaluation

While full advantage should be taken of organic sources of plant nutrients, it is obvious that the role of mineral fertilizers in crop production in developing countries will need to become increasingly important. The formulation and content of manufactured fertilizers are to be given due attention in order to ensure that products are made available to farmers which match their needs in a balanced way. The use of compound fertilizers, both solid and liquid, in combination with novel application methods may overcome many difficulties in improving the nutrient status of soils, subject to training of farmers to use more up-to-date technologies.

A potential contribution of leucaena alley cropping to soil fertility is the nitrogen released from the prunings. The use efficiency of this form of nitrogen can be measured by a direct ^{15}N method and is to be applied to the whole system rather than to a single crop. It was found that the incorporation of pruning N into the soil organic matter may increase the use efficiency when remineralization of the immobilized N occurs in better synchrony with crop demand.

Phosphorus deficiency is a major constraint to crop production in rainfed farming systems in semi-arid zones. A modified Mitscherlich equation has been developed to assess the effect of available moisture on potential yield and thus on crop demand for P. Mathematical models may also be applied to assessing yield responses to nutrient supply, as has been demonstrated for phosphorus management.

Appropriate isotope techniques have proved to be a valuable asset in research on fertilizer use efficiency. They provide quantitative and qualitative answers to important questions related to optimal fertilizer placement, time of application, effects of cultural practices on the uptake of nutrients by plants or their loss into groundwater. These issues are of importance in selecting fertilizer practices adapted to specific ecological conditions and in reducing environmental hazards.

With the use of external sources of nutrients it was again pointed out that optimal management of soil organic matter, crop residues and manures is important to ensure the bio-availability, the cycling and the balance of nutrients in the soil-plant system. Attention to soil organic matter dynamics is particularly important with regard to the uptake of nitrate nitrogen and sulphates. The fact that they have a rather high mobility in soil implies that the processes limiting the rate of uptake are the turnover of organic matter. When comparing local and external plant nutrient sources, attention should be given to aspects of pollution, for instance the occurrence of heavy metals.

When using different sources of plant nutrients it is important that the fertilizer value of such products be evaluated. Chemical analysis can provide a characterization of fertilizer materials. However, a more detailed evaluation relies on greenhouse and field experiments. The experimental data allow for the calculation of relative yield increases or nutrient equivalent in relation to standard sources. Response curves of crop yields to applied rates of nutrients can be used for appraising economic feasibility.

A review was made of integrated plant nutrition in Zimbabwe with special reference to maize, which is the staple food crop in the country. The survey showed that communal farmers are well aware of the need to integrate the use of different sources of plant nutrients as some 20% of them apply compound NPK fertilizers and 80% apply N to their manured crops. Field trials indicate that supplementing the manure with N increases maize yields by 60-80% while supplementing with NPK fertilizer may induce up to a fourfold yield increase. The benefits of biological nitrogen fixation and of locally-available phosphate rock were also shown to have the potential of reducing the cost of purchased fertilizer.

Plant nutrient management in farming systems and in watersheds and in territories

The development of new high-yielding rice varieties continues to increase the potential for greater yields per crop and per unit of land. However, these high-yielding varieties demand more nutrients to sustain vigourous growth adequately and at least to maintain, if not increase, an adequate nutrient base in the soil. Among the plant nutrients, nitrogen is the major one which limits the yield of semi-dwarf rice cultivars. Recent research has addressed N transformation processes in order to minimize losses and increase fertilizer efficiency. It was noted that nitrogen losses are due mainly to ammonia volatilization rather than to denitrification.

The considerable scope which exists for using a system approach in nutrient phosphorus and potassium management was also demonstrated. Besides the three major plant nutrients special attention should also be given to the supply of zinc and sulphur. The improvement of fertilizer efficiency is one of the research priorities to extend the yield frontiers of rice production.

The promotion of integrated plant nutrition systems in France is based on a comprehensive approach involving farmers, extension services, private enterprise and farmers' organizations. The advice to farmers is streamlined and highlights economic, agronomic and environmental benefits. Applications of plant nutrients, from both mineral and organic sources, should be adapted to the requirements and constraints of local farming systems, in accordance with site-specific soil and climatic characteristics and prevailing economic and socio-cultural conditions.

A case study in The Netherlands showed that the combined use of mineral and organic sources of plant nutrients reduced the need for crop protection, reduced nitrogen losses and maintained soil organic matter levels. It was considered to be a more sustainable farming system than with a unilateral use of either mineral or organic sources of plant nutrients, even though some yield losses had to be accepted.

A study in Norway showed that effective plant nutrition management can best be handled at the catchment level. Integrated plant nutrition in a catchment should be combined with soil protection, plant protection and water management. A meaningful approach to combine productivity, sustainability, environment, recreation and cultural landscape values should be based on the catchment of a first order waterway with an area of at least a few square kilometres. The management system must, however, be differentiated according to an intensity classification of production zones and on their specific requirements for environmental protection.

Priorities for FAO's IPNS programme

It was proposed that a judicious combination of mineral and organic sources of nutrients be based on a site-specific assessment of yield targets, nutrient requirements, sources of nutrients, inputs and losses. A balance sheet of nutrient supply could thus be established on the basis of which appropriate fertilizer recommendations could be made. A simple calculation programme, preferably by computer, was proposed for use by advisers and extension staff. The programme would be user-friendly, transparent and flexible but sufficiently precise and structured to be a useful tool toward the formulation of objective and realistic advice.

In reviewing the further development of FAO's IPNS programme the Consultation identified the following components:

- Diagnosis of the issues related to plant nutrition including
    - the stratification of the different environments,
    - the hierarchy of limiting factors,
    - the identification of farmers' objectives and of social rules and constraints.
- Promotion of innovations related to the IPNS approach in
    - reference farms (innovations at field level; alternatives; impact; risk analysis; models for decision making and monitoring),
    - pilot farms (aggregation of innovations in actual farming systems; interactions between livestock, cropping, agroforestry; farmers' appreciation and adoption with regard to labour and cash requirements; risk acceptance; economic motivation).
- Dissemination and extension; role of farmers' organizations through
    - management at village or catchment level,

  - procurement of inputs, insurance, security, marketing, credit,
  - liaison with extension services,
  - feedback from farmers,
  - human resource development at village level.

- ◻ Advice to decision-makers through

  - information-gathering,
  - analysis of impact of innovation,
  - set of alternatives in decision making (regulation, pricing, subsidies, distribution),
  - development of monitoring capacity,
  - development of human resources.

The Consultation reviewed the steps required for the implementation of the above programme:

- ◻ the reactivation of the FAO statutory bodies which advise the Organization on its work in the field of plant nutrition (the Commission on Fertilizers and the FAO/Fertilizer Industry Advisory Committee);

- ◻ provision of the required human resources and expertise with special reference to

  - the agronomic and economic evaluation of plant nutrition practices and plant nutrition sources,
  - the monitoring of environmental concerns,
  - the integration of biological processes in the plant nutrition system,
  - international expertise to synthesize relevant documentation and to support and evaluate field projects;

- ◻ design of detailed field programmes with ranked priorities at regional level;

- ◻ support by donor agencies of IPNS field activities toward sustainable agricultural development;

- ◻ an effective dissemination of appropriate information about the IPNS approach.

The Consultation reflected its considerations on the above programme in its 'Conclusions and Recommendations' as given below.

CONCLUSIONS AND RECOMMENDATIONS

1. To meet the challenge of food security for present and future populations, to provide more employment and better incomes for rural communities, and to conserve natural resources and protect the environment, it is imperative that agricultural production in developing countries be intensified within an overall framework of sustainable development. An important factor in this respect is the maintenance and enhancement of soil fertility through an appropriate application of plant nutrients in order to replenish

the nutrients removed by the harvest of produce and to build up the nutrient status of soils that are inherently infertile or have been depleted.

2. Sources of plant nutrients can be of mineral or of organic origin. It is desirable to make full use of both these sources in an integrated way which is economically and environmentally sound. Special attention should be given to sources of nutrients which may be mobilized by the farmers themselves (manures, crop residues, soil reserves, biological nitrogen fixation, etc.). Minimization of losses and replenishment of nutrients from both internal and external sources are major issues. This approach is the one which is advocated in FAO's Integrated Plant Nutrition System (IPNS) which the Consultation fully supports. This system concurrently pays attention to the interaction with other management practices and addresses farming systems rather than individual crops or fields.

3. While IPNS strives towards the application of balanced inputs, the Consultation stressed that the use of organic sources cannot replace the use of mineral fertilizers. Even though the effects of organic inputs go beyond the nutritional aspects, by contributing to improving soil physical properties and to a better efficiency of fertilizer use, the recycling of organic materials does not suffice to fully replenish the nutrients that are removed by crop harvests. An increased and more efficient use of mineral fertilizers in developing countries is required in the medium term.

4. The Consultation highlighted the very great diversity of organic inputs and the large differences in the quality and availability of these inputs in different farming systems. The Consultation therefore stressed that IPNS advice should refer to nutrient balance sheets and nutrient cycling models at field, farm, village and catchment level. In this way a proper evaluation could be made of plant nutrient losses, mining or accumulation in soil and supply efficiency. In this respect IPNS should be conducted against a background of well characterized soil and climatic conditions.

5. The Consultation endorsed the proposal of establishing a relatively simple but scientifically sound computerized framework to record and process site characteristics, targeted outputs, estimated losses, inputs of both organic and mineral nature, labour and cash requirements, and anticipated benefits. Such a framework would provide a tool for advisers and extension staff to draw up practical recommendations to farmers on a realistic and site-specific basis. The Consultation suggested that the framework be transparent and flexible so as to allow for the incorporation of local experience and to adapt recommendations to prevailing practices.

6. The Consultation identified the need for a quantitative assessment of the decline of food production resulting from the depletion of plant nutrients because of 'mining', erosion and other losses. Such an assessment would give additional weight to the 'balanced inputs' approach of IPNS and offset a detrimental trend of advocating 'low inputs' in developing countries. IPNS should be seen as an approach that advocates an environmentally-sound, efficient and balanced use of plant nutrients.

7. The Consultation stressed that IPNS, besides its technical role, has also important economic, social and cultural dimensions. Hence, its implementation can be ensured only

with active farmers' participation conditioned by economic incentives, improved land tenure and sound agricultural policies.

8. The Consultation felt that the further development of the IPNS programme will need to rely on site-specific diagnoses of constraints, needs and available resources (at field, farm and village level), followed by the design and testing of innovative plant nutrition systems on reference farms and on pilot farms. Positive results should subsequently be extended through the farming community with the help of farmers' organizations and extension services, and support at decision-making level.

9. Considering the more comprehensive scope of the IPNS programme compared to earlier FAO work, which placed emphasis on fertilizer use, the Consultation recommends that the advisory bodies to FAO's work in this field be broadened to include national and international research institutions, agricultural universities, agencies for environmental protection and fertilizer associations.

10. The Consultation recommended that FAO widely disseminate information about its IPNS programme and clearly establish its position on issues of the use of fertilizers and of organic inputs towards sustainable agriculture in developing countries. This information could be prepared in the form of a brochure which would concurrently provide an opportunity to call for cooperation and support.

11. The Consultation considered that the implementation of the IPNS programme will require the provision of an adequate level of resources both in terms of staffing and international expertise.

12. The Consultation recommended that FAO seek cooperation and support from national, regional and international research organizations which address aspects of IPNS. Research results in this field, especially those regarding the quality and effects of organic sources, could be a considerable asset to the IPNS programme.

INTRODUCTORY STATEMENT

Sustainable agriculture: land and water use and the role of local and external inputs for rural development

Land and water use for agriculture varies strongly throughout the world, and there are no marked contrasts between industrialized countries ('the north') and developing countries ('the south'). In the industrialized countries the heavy use of mineral fertilizers, such as in *Northwestern Europe*, may often substantially change, within a few years' time, both in terms of total amounts and relative composition of N, P and K (Angé, 1994). In the *Central and Eastern European* countries there is a sharp decline in mineral fertilizer applications in the present phase of transition to a market economy following the over-liberal applications in the past, especially with regard to nitrogenous fertilizers.

Near areas of concentration of bio-industries, such as the sandy regions of The Netherlands, there is an excessive application of organic fertilizers from solid and liquid manure in addition to large doses of mineral fertilizers. This high supply of plant nutrients results in leakage to ground and surface waters of N, P and heavy metals. The leakage of the latter may be aggravated by airborne acidification that leads to lowering the soil buffering capacity.

In contrast, in certain parts of *Western Europe* such as the hill lands of southern France and Central-South Italy, sizeable areas are being abandoned by high-input farming for economic reasons, with 'nature' or the artificial preservation of traditional low-input farming taking over. On small areas in Western Europe, 'biological', 'dynamic' or 'organic' farming is being practised. In many cases these production systems draw on the accumulated soil fertility of earlier days. The extra labour input required in such farming systems should be compensated by higher prices for the produce being paid by health-sensitive consumer groups. However, with the current stagnation of economic growth, this trend is experiencing problems as well.

In the large-scale grain-based farming systems of the *USA and Canada*, the changes in mineral fertilizer use have been less dramatic, in part because they have never reached the very high levels applied in Western Europe.

In the developing world, the geographic pattern of mineral fertilizer use is also very complex (Table 1). Parts of *Eastern* and *Southeastern Asia*, with year-round cropping, especially for wetland rice with new cultivars on the better soils, have rather high inputs of mineral fertilizers. Yields are now tending to level off or even decline, possibly because of a depletion of P, S, Mg and micronutrients, and on account of less than optimal soil-water

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TABLE 1
Key data on sustainable development per region

	(A) Cereal yield increase between 1965-1990 (%)	(B) Fertilizer consumption 1989/1990 (kg/ha of arable land)	(C) Irrigation of agricultural arable land: 1989/1990 (%)	(D) Projected average population growth rate: 1990-2000 (%)
Sub-Saharan Africa	1.1	9	0.6	3.0
North Africa & Near East	1.5	65	5.5	2.9
East Asia & Pacific	3.4	190	9.9	1.4
South Asia	2.4	69	27.5	1.8
Latin America & Caribbean	2.7	47	20.0	1.8

management (fertilizer 'fatigue'). In *China* the reliance on recycling of farm-level produced organic plant nutrients is rapidly giving way to application of mineral fertilizers, especially urea.

Parts of *Latin America* already have high inputs of mineral fertilizers such as the large-holding farming systems of Central Argentina and South-Central Brazil (wheat, soybean, sugar cane, coffee). Other parts of the subcontinent such as the small-holders' mixed farming areas on the plains of the Amazon region and the mountainous lands of the Andean cordillera and Central America, in contrast, have very low levels of fertilizer application. Plant nutrient depletion in these areas is being avoided, for the time being, by shifting cultivation techniques, the import of organic nutrient sources from nearby forested lands, or by utilizing inherently fertile soils such as Nitisols.

In the *Near East and Northern Africa* sustainable land management problems are more related to the availability and apportioning of irrigation water than with over- or under-use of mineral or organic fertilizers. The soils concerned tend to have high plant nutrient reserves. Many of the irrigated areas in this region receive quite high doses of mineral fertilizers, creating pollution problems. New techniques such as fertigation (i.e., fertilizer dosing in the irrigation water) have the potential for an economic and non-polluting plant nutrition management.

In *Africa, south of the Sahara*, the situation is, however, radically different. Mineral fertilizer consumption is way below that of other regions (Table 1) and even then it is largely restricted to plantation farming (cotton in the Gezira scheme of Sudan; oil palm plantation in Southeast Nigeria; coffee and tea growing in Western Kenya; tobacco and commercial maize growing in Zimbabwe, etc). The amount of mineral fertilizers available to, and used by, small-holders' farming is minimal, which is leading to a serious depletion of the plant nutrient reserves in many places (Stoorvogel and Smaling, 1990). Traditionally, such farming communities could ensure nutrient replenishment from parts of the surrounding landscape, usually hilltops or plateau remnants, that were used only for grazing. These areas can yield manure for the arable fields in the immediate vicinity of the villages (Figure 1).

This Low-External-Input-Sustainable-Agriculture (LEISA) was locally facilitated by dust depositions (Harmattan in West Africa) or siltation of the low lands by seasonal flooding. LEISA was also feasible on naturally rich soils on easily weathering parent materials, such as the Nitisols of the volcanic deposits of Western Kenya, the highlands of Ethiopia, Eastern Zaire and parts of Rwanda, Burundi and Uganda (see map in FAO's World Soil Resources Report 66, 1991). However, with the growth of the rural population and the rising aspirations for well-being, this system of near self-sufficiency is breaking down. Moreover, the high manual labour input required in this farming system is difficult to maintain because of schooling of the children and locally also because of an emerging shortage of manpower (trek to the cities; AIDS affliction). In these situations, the need arises for a more substantial External input of plant nutrients, which in practice will have to be largely in the form of mineral fertilizers, in Balanced composition and with an Adequate amount of Inputs to ensure Sustainable Agriculture (BADEISA).

Especially in situations of marginal land-quality (marginal rainfall conditions; poor physico-chemical soil conditions; poor access conditions) such external inputs have to be combined with judicious use of locally-available organic sources of plant nutrients. Here comes to the fore the subject of our meeting: integrated plant nutrition systems, or IPNS. The need for such an approach in smallholders' farming systems of sub-Saharan Africa is *heightened* by the fact that mineral fertilizers are becoming more expensive at farm gate, with subsidies being abolished under the World Bank/International Monetary Fund-imposed national structural adjustment programmes. Also, the supply to the rural communities is becoming increasingly irregular because of breakdowns in transportation and in credit facilities.

I appeal to all participants to give special attention to the plight of rural Africa in their deliberations.

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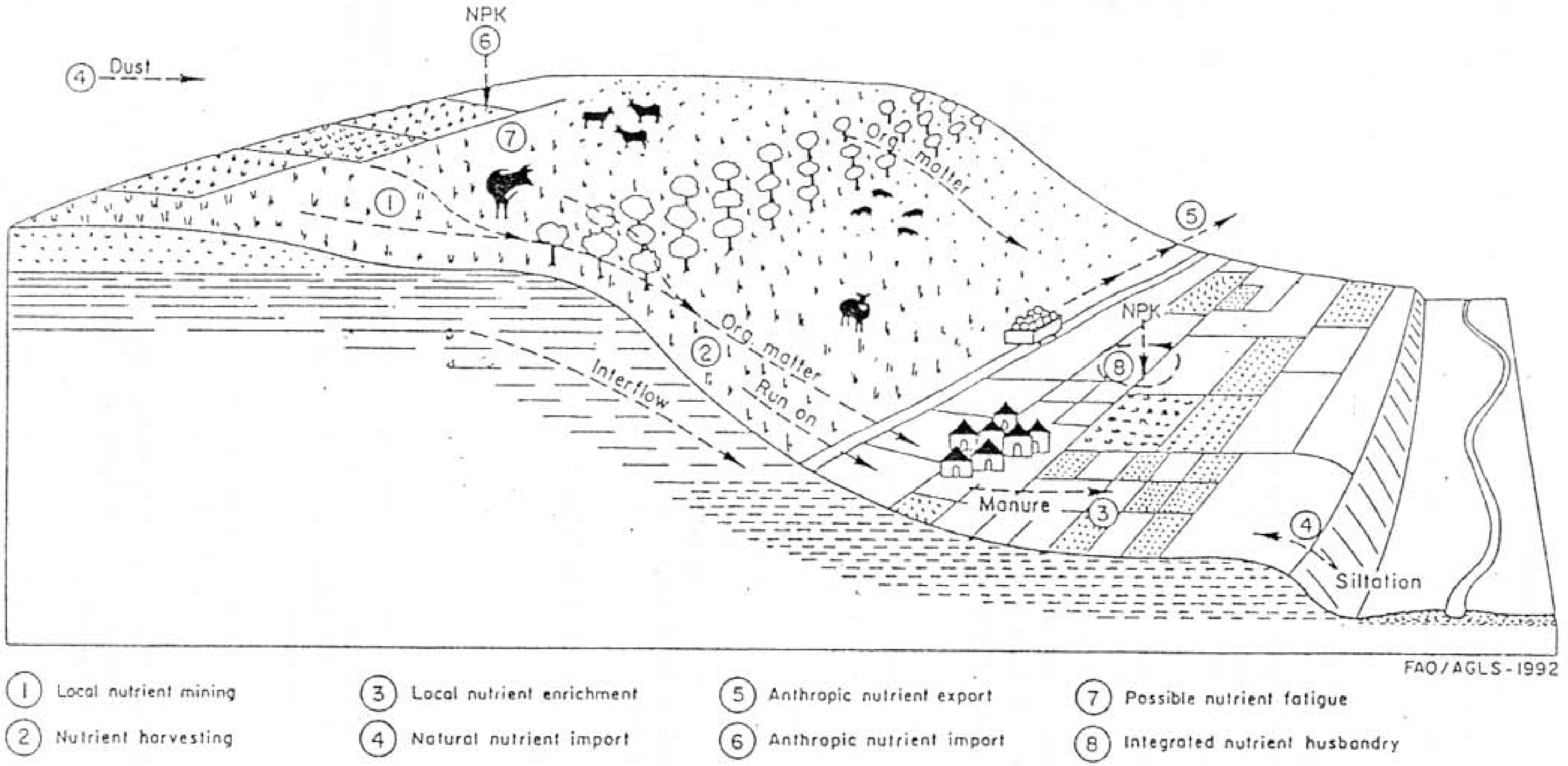
FIGURE 1
Landscape-related nutrient dynamics in mixed farming systems (Sombroek, 1993)



SESSION 1

Importance of plant nutrition for meeting the agricultural product requirements

Development of land use and plant nutrition practices during the last 30 years – consequences for the requirements of crop productivity and plant nutrient supply up to 2010

DEVELOPMENT OF ARABLE LAND AND CROPPED LAND: THE VARIOUS COMPONENTS OF THE INTENSIFICATION OF THE CROPPING SYSTEMS

Arable land includes land put under cultivation, with one or several crops per year, and areas with permanent crops and annual fallow. Cropped land is the sum of the areas cultivated with each crop for all the cropping seasons of the year, including permanent crops. In most countries, arable land has increased in relation to population growth; however, its extent has been reduced due to the expansion of cities and industries as well as due to abandoning of marginal and degraded land. In many developed countries, the intensification of cropping systems has recently created large over-production which has led to the putting back of good land under fallow. The balance between factors increasing the arable land and factors reducing it has varied considerably between the early 1960s and the present. Apart from exceptional situations, the growth of arable land, if any, has decreased during the last 30 years (Table 1).

The development of irrigated areas has helped to put new land under cultivation and has promoted the creation of two cropping seasons per year, where sufficient water is available. In this respect, the introduction of high-yielding varieties (HYV) with shorter growing cycles than those of traditional varieties has largely contributed, in some countries, to a better management of available rainfall. In many countries, the development of cropped areas has been implemented through the reduction of the areas put under fallow (long-term fallow, annual fallow or seasonal fallow). However, fallow has, for a long time, been the traditional way of restoring soil fertility. Hence, when the fallow practice was restricted, farmers had to adopt new methods for the maintenance of the productivity of land.

The intensification of land use has been implemented in different ways, according to the availability of resources, social organizations and cultural backgrounds. In Western Europe and Northern America, the first important innovation for the intensification of cropping systems was the development of cropping patterns, including pastures where leguminous species were fixing nitrogen. The improvement of the integration between livestock systems and cropping systems has streamlined the transfer of plant nutrients from perennial pastures and rangelands to cropped areas, limiting the losses of plant nutrients through a better

PAPER 1.1
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development of the rooting systems in the soil and better management of local sources of plant nutrients. This evolution happened when the arable land *per caput* was larger than 0.4 ha (Belgium, Germany, Netherlands, UK, Switzerland) or even more than 0.8 ha *per caput* (Austria, France).

TABLE 1

Evaluation of the available arable land in some developing countries (from FAO statistics 1970-1990)

Country	Arable land (m^2/*caput*)	
	1990	2010
AFRICA		
Congo	770	530
Kenya	1 030	620
Côte d'Ivoire	2 880	1 850
Niger	4 660	2 240
ASIA		
Bangladesh	790	450
Viet Nam	1 000	680
India	1 980	1 300
Thailand	3 840	3 330
LATIN AMERICA & CARIBBEAN		
Haiti	1 410	990
Guatemala	2 080	1 460
Brazil	5 340	4 330
Argentina	11 400	9 450
NEAR EAST		
Egypt	480	300
Jordan	1 130	660
Algeria	3 010	1 800
Turkey	5 070	3 580

In Asia, the irrigated areas have played a major role in the intensification of land use and the most advanced agrarian civilizations developed in the alluvial areas. Heavy transfers of organic materials, plant nutrients and even topsoils were organized from non-arable lands to irrigated areas. In 1900, the arable land *per caput* in Japan was over 0.23 ha with a cropping index estimated at 1.3; the arable land *per caput* in China was over 0.63 ha with a copping index estimated at 1.1. At the same time, in Indonesia, the arable land *per caput* was over 0.5 ha with a cropping index estimated at 0.7. In India the available land *per caput* was over 1 ha with a cropping index probably lower than 0.5. Rainfed areas were largely used through shifting cultivation and cropping patterns including artificial pastures, and leguminous crops were not promoted at large scale.

During the first decades of the 20th century, in Africa and in Latin America, except in some very populated and limited areas, shifting cultivation with long-term fallow was largely predominant. In Near East and North African countries, extensive rainfed agriculture and existing irrigated areas were sufficient for the required level of food self-sufficiency. Traditional commercial activities supported limited food imports.

However, the favourable effects of biofixation of nitrogen, crop rotation, restitution of crop residues and manures and transfer of nutrients have some limitations. The exports of plant nutrients from cropped areas through harvesting have rapidly exceeded the natural sources of plant nutrients in the most densely populated areas, in particular when an important cash-crop sector was promoted in addition to the food crops. The rapid development of soil erosion and leaching of plant nutrients created by the expansion of cropped areas and the decrease of fallow periods in watersheds has aggravated the deficits of plant nutrients in the balance sheets. Tropical and Mediterranean areas have been much more affected by this mechanism than temperate areas. In China, the balance has been maintained without external inputs up to the early 1960s through massive recycling of urban, domestic and human wastes, and at the cost of very low farmer incomes, even associated with starvation. In India, the food security situation was alarming in the 1960s, like in most populated Asian countries. In Western Europe, farmers began to use mineral fertilizers in the last decades of the 19th century with urban sludges and basic slags. In 1930, in the USA, mineral fertilizers represented 3.5% of the total nutrient supply to crops. N fixation provided 41%, manure 28.6% and crop residues 16% of the supply. In Japan, the use of mineral fertilizers was initiated at the beginning of the 20th century and took off during the 1930s. In Asia, the consumption of mineral fertilizers was really initiated in the 1960s. In Latin America, fertilizer use was initiated in the 1960s, mostly in countries cultivating large areas of sugar cane. In the Near East and Northern African countries, the consumption of mineral fertilizers was initiated in 1950 in Cyprus and Egypt, and in the irrigated areas of Lebanon, Algeria, Tunisia, Israel and Jordan. In the other countries of the region, fertilizer use took off in irrigated areas in the late 1970s. In Africa, the use of mineral fertilizers was significantly developed in Kenya, Swaziland and Zimbabwe in the 1970s (27 to 70 kg/ha) and was initiated, in 1980, in Côte d'Ivoire, Gambia, Lesotho, Malawi and Zambia. In 1990, Congo and Nigeria could be considered as countries approaching the take-off level of mineral fertilizer use (12 kg/ha).

Therefore, historically, the increasing pressure of farmers on the land has forced them to mobilize plant nutrient sources in addition to what was strictly available in the cropped areas, but the evolution of land use and plant nutrient management has been quite different from one country to another.

DEVELOPMENT OF MINERAL FERTILIZER USE IN MOST DEVELOPED COUNTRIES IS RECENT AND THE SUPPLY OF HIGH DOSES OF MINERAL FERTILIZERS IS LIMITED TO FEW COUNTRIES

In the developed countries, in North America, in Europe and in Asia and the Pacific, the development of the use of mineral fertilizers is very recent. In 1950, the consumption of $(N+P_2O_5+K_2O)$ fertilizers per ha was already 390 kg in The Netherlands and 262 kg in Belgium and Luxembourg. Fertilizer consumption was 167 kg/ha in the Federal Republic of Germany, 139 kg/ha in Norway, 131 kg/ha in the German Democratic Republic, 118 kg/ha in Japan, 112 kg/ha in Switzerland and UK, 96 kg/ha in Denmark. The average dose of mineral fertilizers was quite limited in Finland, France, Ireland and Sweden (50-57 kg/ha). Fertilizer consumption was in the take-off stage in Austria, Czechoslovakia, Italy, Poland, Portugal and the USA (20 to 35 kg/ha). In the other European countries and in Canada fertilizer usage was at the level of present consumption in Latin America. The average fertilizer dose in Europe was doubled between 1950 and 1960 (45 to 83 kg/ha) and consumption went over 150 kg/ha in non-Mediterranean countries except in France (92 kg/ha) and Austria (116 kg/ha). However, fertilizer consumption was still very low at that time in North America. In Japan, the fertilizer dose went up to 269 kg/ha in 1960.

In Europe, the most impressive development of fertilizer use occurred between 1965 and 1975 through the development of the European Economic Community and through the take-off of fertilizer use in Centrally Planned Economies (113 to 193 kg/ha). The same evolution occurred in the USA (57 to 85 kg/ha), while in Japan, the development of fertilizer use was regular (315 to 354 kg/ha). In 1980, the average dose of fertilizer reached the maximum observed until now in The Netherlands (707 kg/ha), in Belgium (538 kg/ha), in Germany (582 kg/ha), and in Switzerland (448 kg/ha). However, the very high-level of fertilizer use observed in the first group of countries are an exception in Europe and consumption at

FIGURE 1
Western Europe - arable land *per caput* and fertilizer use 1950-1990

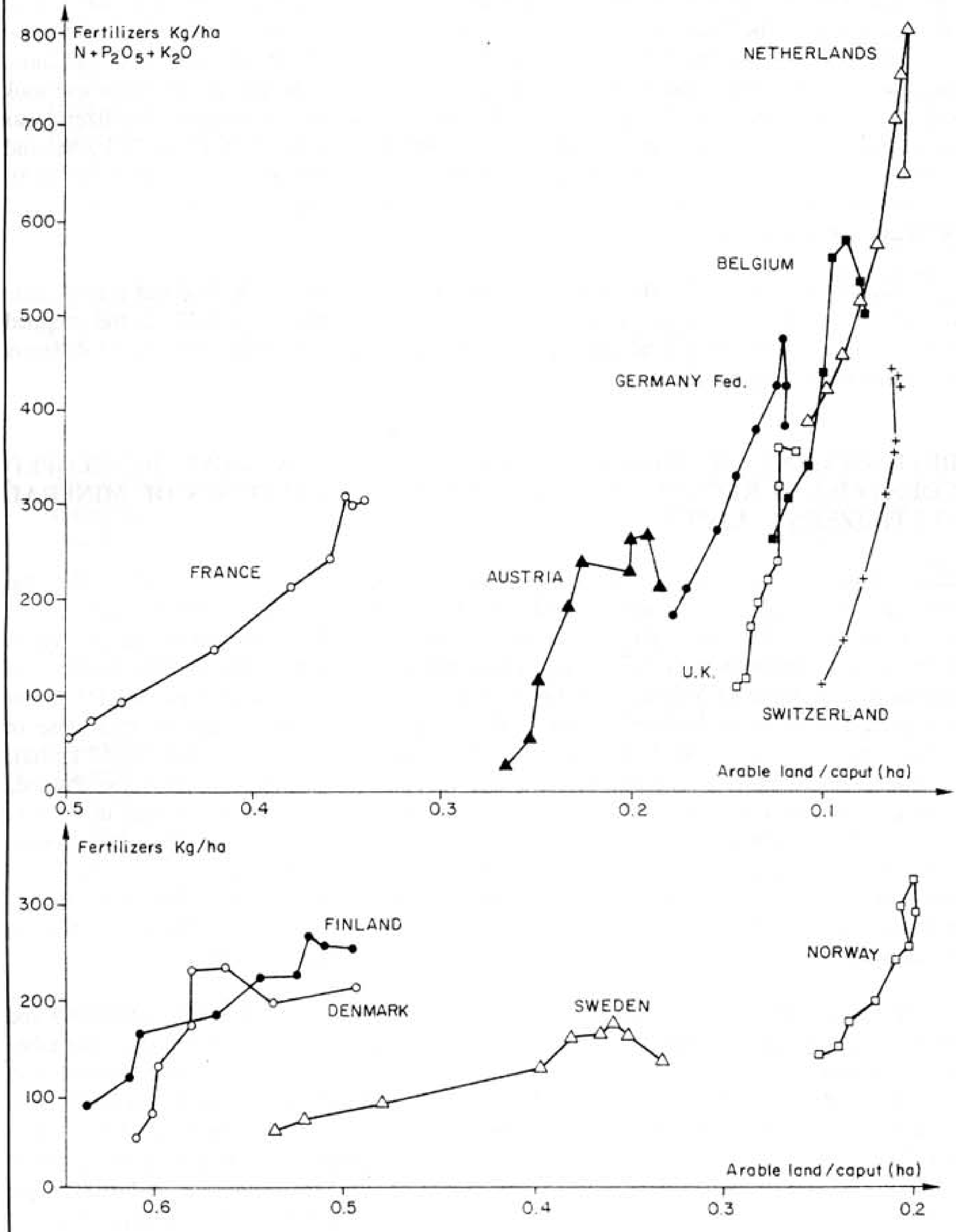


TABLE 2

Developed countries - progress of agricultural intensification through fertilizers

Arable land/*caput* (ha)	1950	1955	1960	1965	1970	1975	1980	1985	1990
Canada	2.626	2.512	2.313	2.111	1.965	1.908	1.878	1.826	1.733
USA	1.213	1.146	1.024	0.920	0.929	0.871	0.837	0.794	0.762
Japan	0.060	0.067	0.058	0.054	0.047	0.040	0.037	0.035	0.034

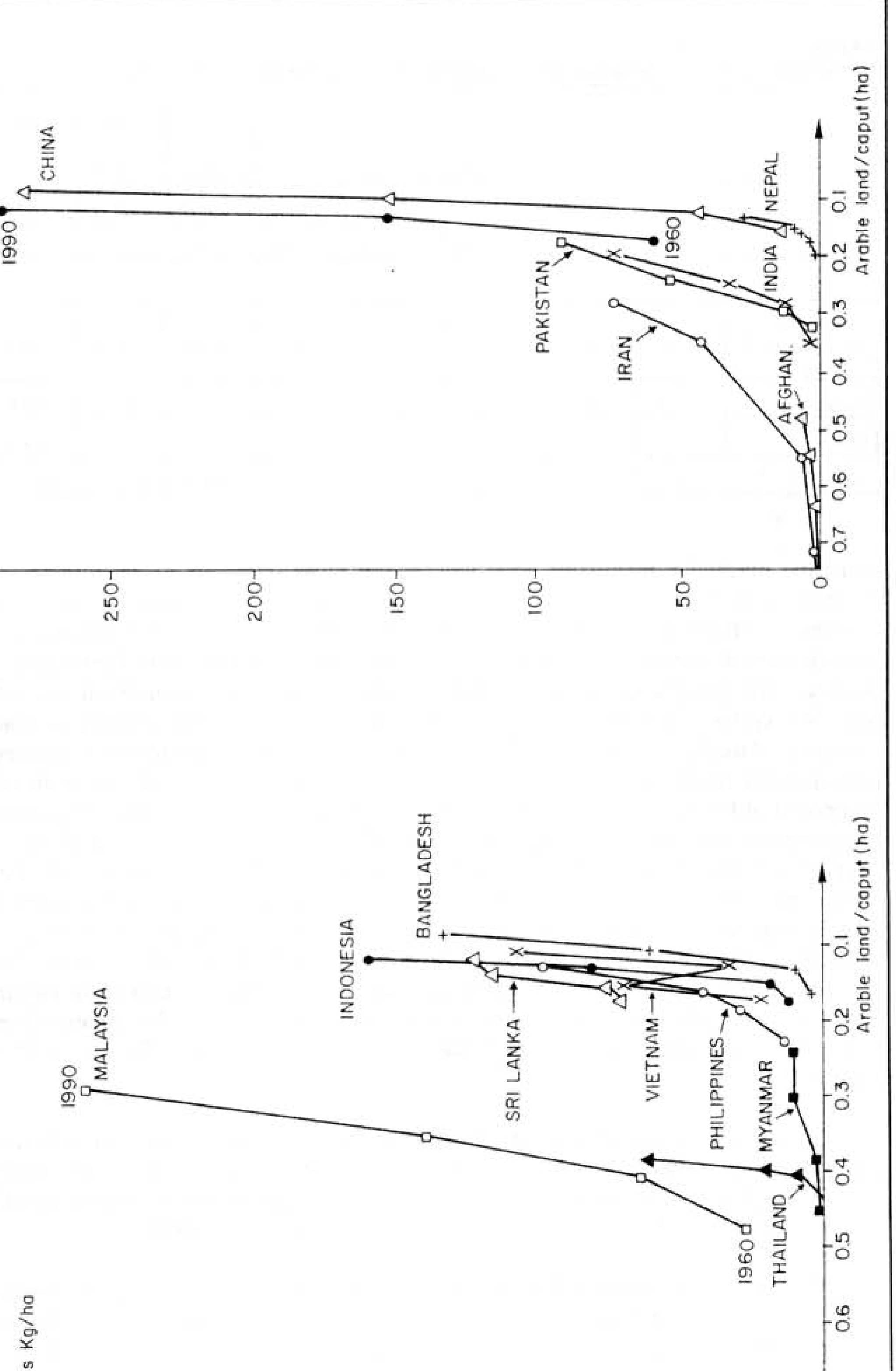
Fertilizer ($N+P_2O_5+K_2O$) kg/ha	1950	1955	1960	1965	1970	1975	1980	1985	1990
Canada	5.5	6.4	6.8	12.0	17.4	28.6	40.3	50.6	45.1
USA	23.3	31.1	37.1	56.5	76.0	84.7	109.9	93.7	97.9
Japan	118.5	165.8	268.5	315.8	354.8	354.0	272.1	427.5	388.6

that time reached a maximum level well below those observed in the former countries in Western and Northern Europe, Centralized Economies and moreover in Mediterranean countries. Thus, the second group of European countries, with regard to fertilizer consumption is composed of the Czechoslovakia, the former German Democratic Republic, Norway, UK and France, with a maximum registered average consumption rate between 310 and 340 kg/ha. The third group of European countries in this respect is composed of Hungary, Austria, Denmark, Poland and Bulgaria, with a maximum registered average consumption rate between 225 and 290 kg/ha. The fourth group of European countries is composed of Finland, Italy Greece, Sweden and Albania, with a maximum registered average consumption rate between 150 and 190 kg/ha. The last group of countries applied a maximum average fertilizer dose lower than 150 kg/ha (Romania: 142; Yugoslavia: 125; Portugal 87; Malta: 66). The situation of Ireland and Iceland is special as mineral fertilizers have been largely supplied to permanent pastures (average dose 100-120 kg/ha). A considerable part of fertilizer consumption in Denmark, Germany, The Netherlands, UK, France, Switzerland should not be accounted for arable land as it has been supplied to permanent pastures, which in fact substantially lowers the supply of fertilizers to arable land. The relationshop between arable land *per caput* and fertilizer use (1950-1990) in Western Europe is illustrated in Figure 1.

On average the use of mineral fertilizers reached as much as 51 kg/ha in Canada in 1985 and 110 kg/ha in the USA in 1980. The maximum average dose of fertilizers applied in one year was 428 kg/ha in Japan in 1985. Fertilizer consumption has decreased in all European countries except in Albania, Portugal, Greece and Spain since 1985.

The rapid and massive development of fertilizer use in Europe and North America (Table 2) has created considerable surpluses for exports. Furthermore, the fast increase of the consumption of animal products has enhanced the consumption of fertilizers since the production of a calorie or protein unit through livestock requires a considerable amount of feedstuff and entails considerable energy and nitrogen losses. Hence, the development of the use of the land, the evolution of cropping systems and the modification of plant nutrient management in these countries have not been generated by the basic requirements of food self-sufficiency. The forces pressing on the intensification of land use and fertilization are different in developing countries.

FIGURE 2
Asia - arable land *per caput* and fertilizer use 1960-1990



DEVELOPMENT OF ARABLE AND CROPPED LAND IN ASIA - INTERACTIONS WITH THE DEVELOPMENT OF MINERAL FERTILIZER USE

In Asia, the total population still doubles every 30 years. Except in the steppes of Mongolia and in the rice paddies and humid forests of Indonesia and Thailand, the development of arable land during the last 30 years has been very limited. A significant increase in arable land has occurred in Nepal and in Sri Lanka at a high cost for the environment. In other cases, the arable land *per caput* has fallen dramatically during the last 30 years and this trend will continue over the next 40 years. The expansion of the cropped area through the development of irrigation and double cropping has limited the impact of the reduction of the arable land *per caput* in many countries. The relationship between arable land *per caput* and fertilizer use (1960-1990) in Asian countries is shown in Figure 2. Fertilizer use and cropping intensity are reflected in Table 3.

In North Asia, the area used for annual crops has grown significantly during the last 30 years. In China, after a limited increase of this area until 1975, the situation stabilized. In India, the area used for annual crops increased slowly to 111% of the area cropped in 1960, and has remained stable since 1985. In Pakistan, the increase of the annually cropped area was regular, and in 1990 this area had increased by 40% since 1960. Also in Nepal the increase of the annually cropped area rose steadily, and in 1990 this area had increased by 73% of the corresponding area in 1960. In the Democratic People's Republic of Korea, the area annually cropped, after a rapid increase in the 1960s, reached stability at 38% over the 1960 level in 1985; it has recently increased by 50% of the corresponding area in 1960. The same development occurred in Iran, with a stability level of 15 years at 52% over the 1960 level and a recent increase of 83% of the corresponding area in 1960. In Bhutan, the increase of the annually cropped area in 1980 had risen by 43% of the 1960 level and did not progress further. In Mongolia, the increase of the cropped area occurred in two steps: 30% from 1960 to 1965 and 63% from 1975 to 1985. In Afghanistan, the civil unrest has provoked a 28% decrease of the annually cropped area for the last 15 years.

In Japan and in the Republic of Korea, the annually cropped areas have been decreasing for many years. These dynamics started in the 1950s in Japan, and in the early 1980s in the Republic of Korea. During 30 years, Japan has lost 48% of the area cropped in 1960 and the Republic of Korea 23%.

In the northern part of South Asia, the development of the annually cropped area was moderate compared to what had happened in the North Asian countries mentioned above. In Bangladesh, in the course of 30 years, the annually cropped area increased by 32%, but there has been no progress for the last 10 years. In Myanmar, the annually cropped area increased by 26% and there has been no progress for the last 15 years. In Laos, the increase of the annually cropped area was 18% in the course of 30 years but has been insignificant for the last 15 years. In Cambodia the civil unrest reduced the cropped are by 50% in 1975 and has limited the recuperation of the situation which prevailed in 1970.

In the southern part of South Asia, the increase of the annually cropped are has been in the same range as in Indonesia and the Philippines, but in Indonesia the increase has been, and still is, constant since 1960 (43% additional land in 1990), while in the Philippines no further progress has been registered since 1975 (33% over the 1960 level). In Malaysia, after a rapid expansion until 1975 (50% over the 1960 level), the annual cultivation of the land

TABLE 3
Fertilizer use on annually cropped area and cropping intensity index

ASIA	1960				1965				1970				1975				1980				1985				1990			
Country	Arable Land — Caput	Cropped Land — Caput	Cropping Index	Fert. Kg/ha	Arable Land — Caput	Cropped Land — Caput	Cropping Index	Fert. kg/ha	Arable Land — Caput	Cropped Land — Caput	Cropping Index	Fert. kg/ha	Arable Land — Caput	Cropped Land — Caput	Cropping Index	Fert. kg/ha	Arable Land — Caput	Cropped Land — Caput	Cropping Index	Fert. kg/ha	Arable Land — Caput	Cropped Land — Caput	Cropping Index	Fert. kg/ha	Arable Land — Caput	Cropped Land — Caput	Cropping Index	Fert. kg/ha
Afghanistan	0.742	0.346	46.7	0.1	0.695	0.333	47.8	0.1	0.832	0.274	43.4	2.4	0.563	0.267	47.4	4.5	0.541	0.229	42.2	6.2	0.545	0.187	34.4	9.1	0.475	0.153	33.3	7.0
Bangladesh	0.165	0.196	118.2	2.4	0.152	0.194	127.8	6.0	0.133	0.183	137.2	15.7	0.116	0.166	142.3	23.6	0.101	0.146	144.5	45.7	0.088	0.134	151.8	59.2	0.078	0.118	150.4	100.4
Bhutan	0.084	0.090	106.2	0	0.090	0.092	102.3	0	0.090	0.098	108.8	0	0.089	0.098	109.8	0.4	0.088	0.092	103.6	0.4	0.081	0.084	103.6	0.3	0.075	0.077	102.7	0.3
Cambodia	0.312	0.419	107.1	0.5	0.454	0.426	94.0	0.7	0.419	0.377	89.8	1.0	0.408	0.168	41.1	0	0.455	0.256	56.2	2.6	0.399	0.222	55.6	0.7	0.351	0.237	67.7	2.6
China PR	0.157	0.204	130.4	7.0	0.143	0.193	135.5	25.1	0.123	0.171	139.6	43.4	0.107	0.158	147.9	68.7	0.099	0.141	142.6	154.1	0.090	0.122	135.3	173.1	0.082	0.124	149.4	283.4
India	0.351	0.316	90.2	2.1	0.322	0.294	91.0	4.8	0.292	0.276	94.3	13.7	0.266	0.251	94.4	20.8	0.240	0.227	94.8	32.8	0.216	0.207	96.1	50.3	0.194	0.192	99.2	74.3
Indonesia	0.149	0.134	89.9	8.0	0.136	0.132	96.7	5.4	0.124	0.125	100.8	13.3	0.118	0.111	94.5	24.8	0.103	0.110	106.8	60.2	0.095	0.103	107.7	94.4	0.086	0.102	118.7	118.1
Iran	0.710	0.286	40.2	0.92	0.626	0.312	49.8	2.3	0.538	0.298	55.1	6.1	0.476	0.278	58.6	20.4	0.338	0.260	77.1	41.7	0.296	0.222	74.9	62.4	0.258	0.212	82.3	79.7
Japan	0.058	0.073	126.9	268.5	0.054	0.063	116.1	315.8	0.047	0.047	98.8	354.8	0.040	0.037	92.6	354.0	0.037	0.033	90.2	272.1	0.035	0.031	88.7	427.5	0.034	0.029	84.4	388.6
Korea DR	0.170	0.157	92.2	59.1	0.157	0.159	101.4	88.7	0.143	0.158	109.9	154.5	0.136	0.151	111.4	201.9	0.123	0.134	109.5	325.5	0.123	0.118	95.8	358.4	0.113	0.121	106.5	334.8
Korea R	0.080	0.108	133.8	150.8	0.077	0.113	145.7	149.4	0.069	0.100	143.9	245.0	0.061	0.087	143.7	386.2	0.054	0.067	124.2	365.7	0.049	0.056	114.4	376.5	0.045	0.050	110.2	456.0
Laos	0.374	0.302	80.9	0	0.342	0.405	118.4	0	0.307	0.269	87.4	2	0.278	0.249	89.3	0	0.269	0.262	97.6	4.6	0.246	0.223	40.4	2.2	0.217	0.192	88.6	2.2
Malaysia	0.237	0.068	28.7	21.4	0.190	0.068	36.0	26.5	0.114	0.071	62.6	48.9	0.109	0.069	63.8	59.1	0.073	0.059	81.2	105.1	0.067	0.053	87.0	125.2	0.058	0.042	72.2	195.1
Mongolia	0.585	0.344	58.7	0	0.850	0.423	49.7	0	0.610	0.348	57.0	2.7	0.572	0.306	53.6	3.6	0.711	0.339	47.7	6.8	0.710	0.339	47.8	14.0	0.628	0.307	48.9	12.4
Myanmar	0.443	0.277	69.0	0.6	0.410	0.307	74.8	0.9	0.372	0.267	71.8	2.1	0.315	0.253	80.2	5.5	0.283	0.277	80.3	10.0	0.256	0.214	83.5	19.3	0.230	0.187	81.3	7.1
Nepal	0.191	0.219	114.7	0	0.177	0.215	121	0.6	0.172	0.213	124.1	2.5	0.178	0.202	113.4	5.2	0.155	0.187	121.0	9.5	0.146	0.187	128.0	17.3	0.136	0.189	139.1	27.6
Pakistan	0.326	0.248	75.9	2.5	0.334	0.246	73.5	3.7	0.291	0.223	76.7	14.6	0.262	0.191	72.7	27.9	0.235	0.185	79.0	53.7	0.196	0.161	82.3	73.3	0.165	0.145	87.5	91.3
Philippines	0.236	0.217	91.8	8.5	0.223	0.194	87.3	12.3	0.190	0.178	93.5	21.0	0.165	0.194	117.6	23.1	0.147	0.168	114.8	30.6	0.125	0.147	117.5	35.8	0.112	0.129	116.6	73.8
Sri Lanka	0.073	0.067	91.8	54.6	0.068	0.059	86.3	51.2	0.069	0.076	110.4	53.1	0.058	0.080	136.3	37.7	0.050	0.065	127.7	88.1	0.047	0.076	162.5	107.9	0.045	0.068	150.6	90.0
Thailand	0.388	0.267	69.0	1.6	0.376	0.267	71.1	2.7	0.352	0.261	74.0	5.9	0.367	0.288	78.4	10.8	0.355	0.298	83.8	16.5	0.341	0.305	89.5	20.8	0.341	0.280	82.1	47.2
Viet Nam	0.159	0.165	103.5	14.9	0.147	0.157	107.2	13.0	0.133	0.139	104.6	51.3	0.120	0.130	108.3	53.0	0.113	0.149	132.4	23.8	0.099	0.132	134.1	59.3	0.086	0.127	146.5	81.4

decreased significantly (32% the 1960 level). On the contrary, in Sri Lanka and in Thailand, the annually cropped areas have increased greatly in the course of 30 years reaching, in 1990, 74% and 114% respectively over the 1960 level.

The development of irrigation, and primarily the development of the use of mineral fertilizers, has markedly determined the modification of land use. The comparison between groups of countries reveals major trends which are quite substantial for taking decisions on the development of land use, the monitoring of the development of the use of mineral fertilizers and the planning of new fertilizer manufacturing capacities.

Mineral fertilizers are used for annual and perennial crops. In some countries, the use of fertilizers on perennial crops is very evident. However, at present, it is not possible to distinguish the amount of fertilizers used on each category of crop from 1960 onwards. Thus, only the total consumption of plant nutrients ($N + P_2O_5 + K_2O$) per country will be considered here. The use of mineral fertilizers is also quite different in irrigated and non-irrigated areas. The corresponding distribution of fertilizers per country is unknown, which hampers the diagnosis of the constraints and the potential for the intensification of agriculture. The analysis presented below should be elaborated for each agricultural region of a country.

Figures 3 to 13 present the evolution of mineral fertilizer use per unit of annually cropped land, in selected countries, from 1960 to 1990. These figures also present the evolution, in the same period, of arable land *per caput*, by country, compared to the evolution of annually cropped land *per caput*. The ratio between these two variables is indicated by iso-lines.

The development of mineral fertilizer use is very recent in North Asia. In China, like in Nepal and Iran, the rate of 25 kg/ha was reached when the cropped land *per caput* decreased to 0.19 ha. In Pakistan and in India, this rate was reached when the cropped land *per caput* decreased to 0.22 ha. In China, the take-off of fertilizer consumption occurred in 1965 while in India, Iran and Pakistan it took place in 1975 and in Nepal in 1990. The take-off has not yet occurred in Afghanistan, Bhutan and Mongolia. In China, the cropping intensity was stabilized to 1.5 thanks to the increase of fertilizer use from 154 kg/ha to 283 kg/ha between 1980 and 1990. The same favourable evolution was obtained in India through the increase of fertilizer use from 33 kg/ha to 74 kg/ha, and in Pakistan from 53 kg/ha to 91 kg/ha during the same period, significantly improving the nutritional status of the population. In Nepal, the development of fertilizer use from 10 to 28 kg/ha could not prevent farmers from increasing cropping intensity from 1.15 to 1.35 while the decreasing trend of the cropped land *per caput* was eliminated. **Thus, in North Asia, where possibilities of double cropping through natural water supply by rainfall are limited, increased use of mineral fertilizers has obviously limited the pressure of agriculture on the land while assuring food self-sufficiency. However, limits of the present methods of plant nutrition appear in Pakistan, China and the Democratic People's Republic of Korea, which press for new research efforts in agriculture.**

In the northern part of South Asia, mineral fertilizer consumption took off in 1950 in Sri Lanka, in 1968 in Viet Nam, in 1975 in Bangladesh, and in 1985 in Myanmar, but was not implemented in Cambodia and in Laos. The level of 25 kg/ha of mineral fertilizer was reached when the cropped land *per caput* dropped below 0.17 ha in Bangladesh, 0.15 ha *per*

FIGURE 3
Fertilizer use on annually cropped area and cropping intensity index – Thailand

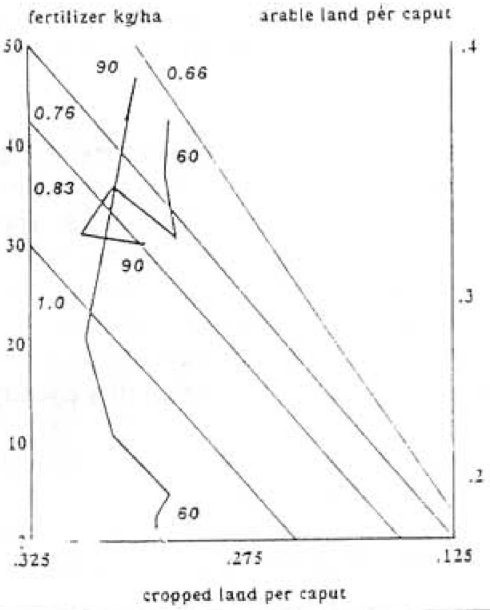


FIGURE 5
Fertilizer use on annually cropped area and cropping intensity index – Philippines

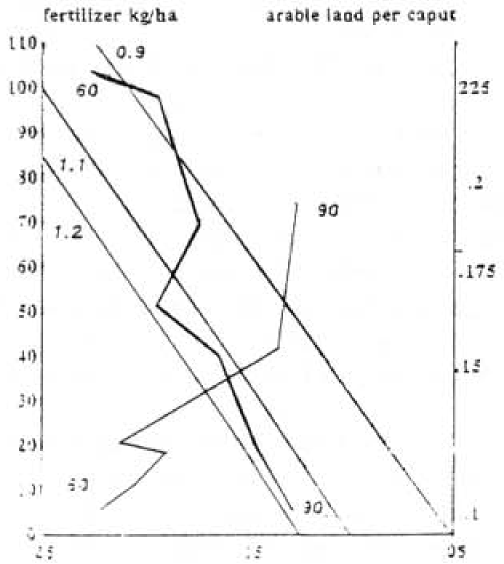


FIGURE 4
Fertilizer use on annually cropped area and cropping intensity index – Myanmar

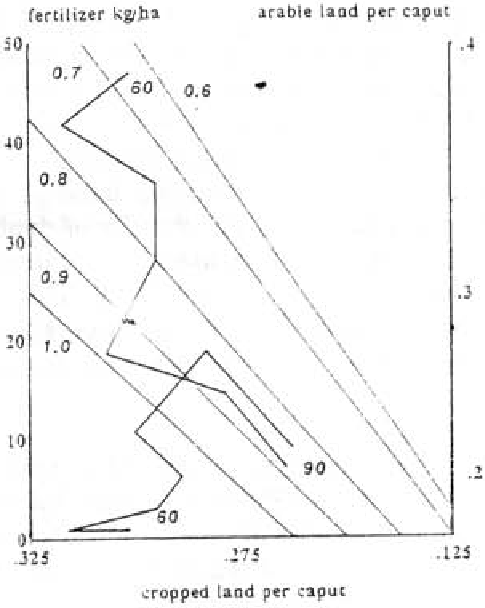


FIGURE 6
Fertilizer use on annually cropped area and cropping intensity index – Indonesia

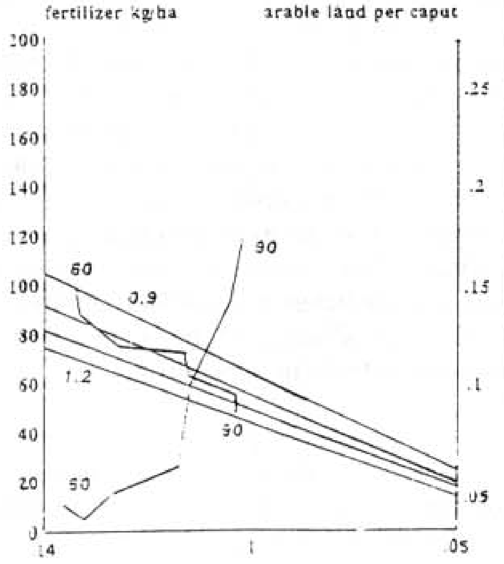


FIGURE 7
Fertilizer use on annually cropped area and cropping intensity index – India

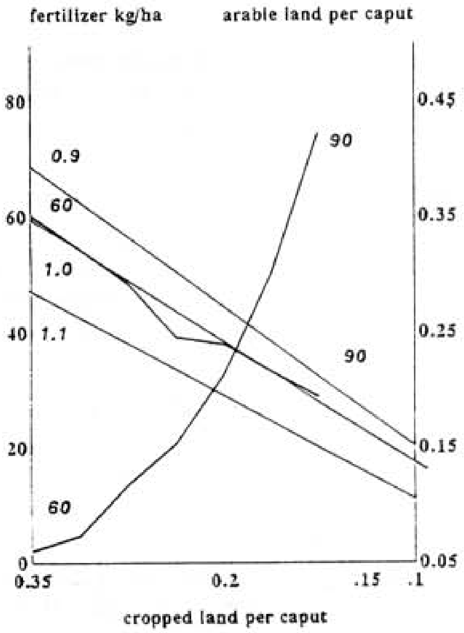


FIGURE 9
Fertilizer use on annually cropped area and cropping intensity index – Nepal

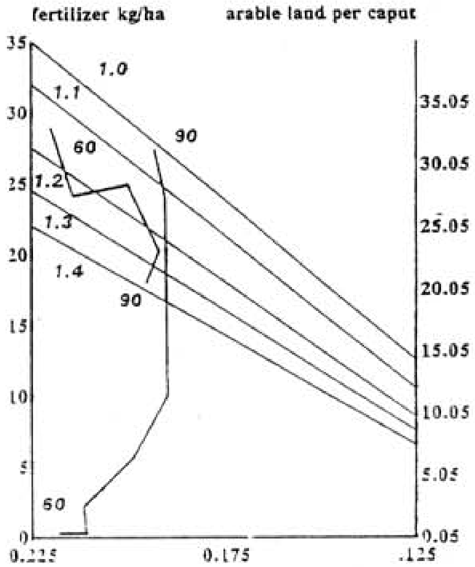


FIGURE 8
Fertilizer use on annually cropped area and cropping intensity index – Pakistan

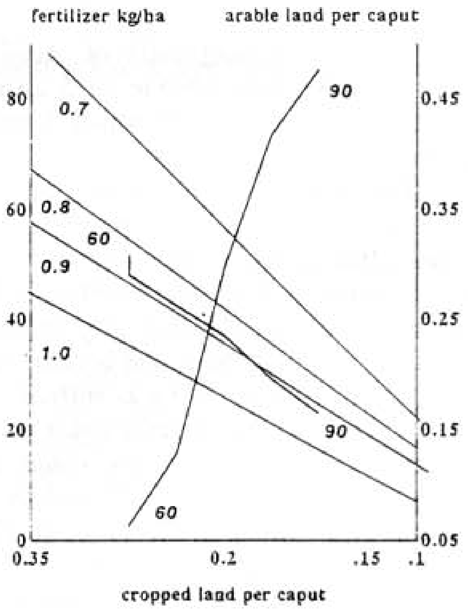


FIGURE 10
Fertilizer use on annually cropped area and cropping intensity index – Iran

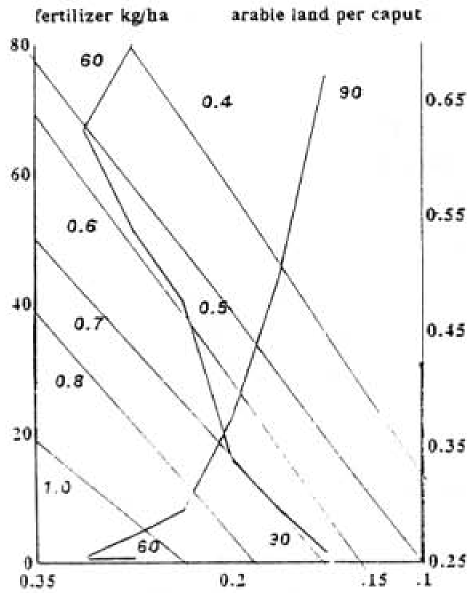


FIGURE 11
Fertilizer use on annually cropped area and cropping intensity index – Viet Nam

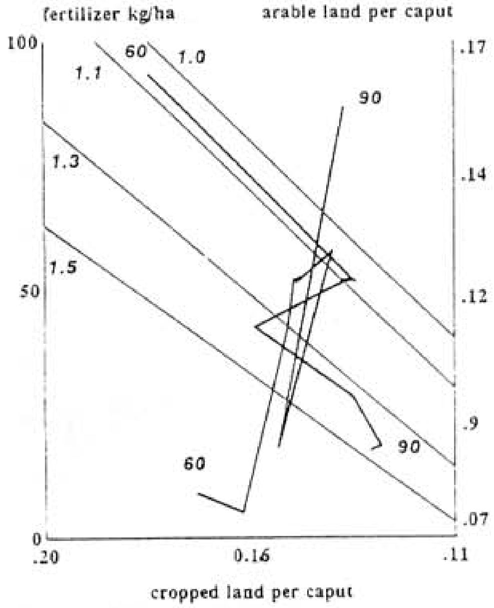


FIGURE 12
Fertilizer use on annually cropped area and cropping intensity index – Bangladesh

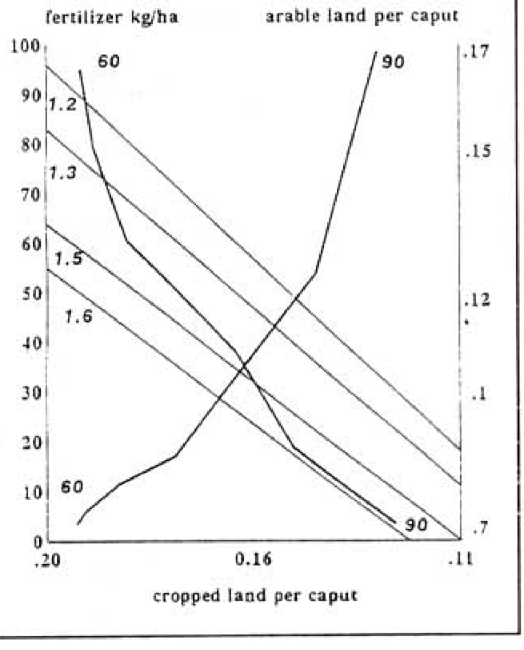
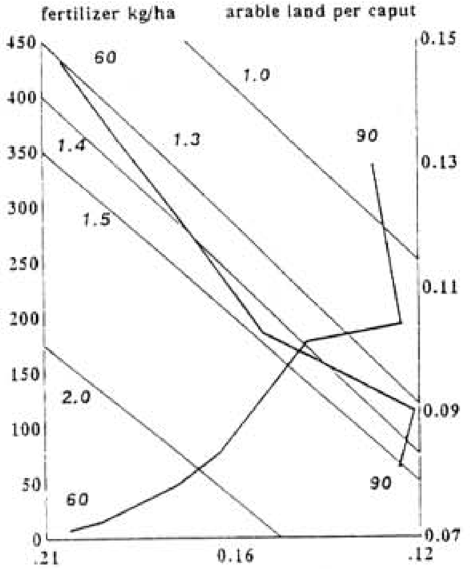


FIGURE 13
Fertilizer use on annually cropped area and cropping intensity index – China



caput in Viet Nam, 0.13 ha *per caput* in Sri Lanka. The climatic conditions are more favourable than in North Asia which reduces the pressure for external inputs where land is scarce.

However, the stagnation of fertilizer use in Sri Lanka from 1960 to 1975 created unfavourable conditions in which farmers increased the cropping index from 0.9 to 1.36. The rapid development of fertilizer use up to 1987 stopped the increasing use of the land (108 kg/ha); further degradation of the conditions of fertilizer distribution led farmers to increase the cropping intensity index to 1.5. In Viet Nam, the development of fertilizer use up to 1970 was sufficient to maintain the cropping intensity index at 1.1 even if the cropped land *per caput* had sharply decreased. Heavy difficulties in fertilizer procurement from 1975 to 1985 brought about a drastic increase of the cropping intensity index (1.45), while the cropped land *per caput* was stabilized. The recent development of fertilizer use (81 kg/ha) has frozen the degradation of cropping conditions. In Bangladesh, there is no doubt that development of fertilizer use since 1975 has limited the dramatic increase in the pressure on the land. However, this development is insufficient. The very high population growth rate, the scarcity of the land and the already very high cropping intensity index threaten the food security in one of the poorest countries. The same unfavourable evolution is ongoing in Myanmar where the cropping intensity and the pressure on the land are still rather limited. **Thus, this region is facing major difficulties and the monitoring of integrated land use and fertilizer use will need particular attention in the future.**

In South Asia, the cropping intensity index is rather low, even though in most ecological regions in this area the natural rainfall and the availability of irrigation create the opportunity of having two cropping seasons per year. In Malaysia, the rate of 25 kg/ha of fertilizers was reached when the cropped land *per caput* was 0.07 ha, but most of the fertilizers are applied to permanent crops. In the Philippines, this consumption level was reached when the cropped area *per caput* was limited to 0.18 ha. In Indonesia, thanks to the fertility of soils in Java, the excellent water management and the high technical skills of farmers, the rate of 25 kg/ha of fertilizers was only necessary when the cropped area *per caput* was close to 0.11 ha. In Thailand, because of the Government's and farmers' objectives of massive rice exports 25 kg/ha of fertilizer were supplied when the cropped land *per caput* decreased to a level of 0.31 ha. The take-off of fertilizer use took place in 1965 in Malaysia, in relation to the extraordinary development of permanent crops. Fertilizer consumption took off in 1975 in the Philippines and in Indonesia, but the consumption was stagnant in the Philippines up to 1987, while it has progressed regularly and rapidly in Indonesia. In Thailand, fertilizer use took off in 1987. In Malaysia, the cropping intensity has been stabilized close to 0.9 since 1975, but the cropped land *per caput* declines sharply because the productivity has not been improved. In the Philippines, the cropping intensity has stabilized at 1.2 since 1985, but the cropped land *per caput* has decreased sharply in the meantime; the development of mineral fertilizer use has been insufficient. In Indonesia, the efficiency of mineral fertilizer use has been remarkable. In Thailand, the cropped land *per caput* has been stabilized but the cropping intensity has been increased. **In South Asia, the efficiency of mineral fertilizers is low. In this region, with the exception of the Philippines, programming the intensification of agriculture has had visibly good results.**

In view of the above, in North Asia, the rapid development of fertilizer use contributed to a large extent to limiting the expansion of arable land and cropping intensity, which maintained a minimum space for fallow and temporary pastures. This equilibrium was threatened in most countries by an insufficient efficacy of mineral fertilizers on crop yields. In South Asia, arable land was more widely available; however, mineral fertilizers have also generally contributed to limiting the expansion of arable land. The efficacy of mineral fertilizers is apparently lower in South Asia than in North Asia. In the northern part of South Asia, the monitoring of land use and fertilizer use needs major improvements. In all countries where civil unrest or political difficulties have limited the proper development of fertilizer use, cropped areas were immensely expanded, thus compensating for low yields, or population migration.

TABLE 4

Latin America and Caribbean – arable land *per caput* and fertilizer use

Country	1970		1975		1980		1985		1990	
	Arable land *per caput* (ha)	Fert. kg/ha	Arable land *per caput* (ha)	Fert. kg/ha	Arable land *per caput* (ha)	Fert. kg/ha	Arable land *per caput* (ha)	Fert. kg/ha	Arable land *per caput* (ha)	Fert. kg/ha
Argentina	1.386	3	1.326	2	1.247	3	1.189	4	1.140	4
Barbados	0.138	173	0.134	127	0.133	176	0.130	101	0.128	91
Belize	0.375	73	0.372	44	0.356	36	0.319	46	0.294	88
Bolivia	0.518	1	0.671	1	0.605	1	0.541	2	0.483	3
Brazil	0.562	19	0.559	33	0.586	59	0.559	42	0.534	43
Chile	0.423	32	0.398	22	0.380	31	0.358	47	0.332	69
Colombia	0.235	29	0.213	42	0.193	60	0.177	69	0.163	101
Costa Rica	0.285	100	0.250	134	0.221	145	0.198	154	0.180	203
Cuba	0.307	152	0.734	106	0.331	165	0.325	179	0.316	199
Dominican Rep.	0.257	33	0.249	58	0.249	36	0.229	41	0.212	50
Ecuador	0.422	13	0.367	13	0.315	29	0.273	28	0.244	29
El Salvador	0.174	104	0.155	144	0.160	83	0.154	116	0.144	106
Granada	0.170	0	0.170	0	0.156	0	0.161	0	0.165	0
Guatemala	0.296	30	0.272	34	0.253	49	0.230	52	0.208	66
Guyana	0.525	27	0.516	34	0.652	12	0.627	25	0.628	33
Haiti	0.179	0	0.174	2	0.166	0	0.153	4	0.141	4
Honduras	0.586	16	0.531	12	0.480	16	0.406	13	0.352	18
Jamaica	0.134	87	0.129	70	0.124	66	0.116	44	0.112	116
Mexico	0.438	23	0.385	45	0.384	50	0.311	69	0.281	70
Nicaragua	0.587	21	0.511	16	0.450	43	0.388	50	0.334	28
Panama	0.355	39	0.312	47	0.284	55	0.261	45	0.240	58
Paraguay	0.390	10	0.430	1	0.551	4	0.589	5	0.619	9
Peru	0.213	30	0.211	33	0.204	34	0.190	20	0.180	41
Suriname	0.102	56	0.118	65	0.139	33	0.162	188	0.180	26
Trinidad	0.103	88	0.114	61	0.107	69	0.100	60	0.095	57
Uruguay	0.507	49	0.508	33	0.497	56	0.441	45	0.436	54
Venezuela	0.330	17	0.283	39	0.250	64	0.218	127	0.192	138

DEVELOPMENT OF ARABLE AND CROPPED LAND IN LATIN AMERICA AND THE CARIBBEAN AND UNEQUAL DEVELOPMENT OF FERTILIZER USE

In Latin America and the Caribbean, the favourable situation of food self-sufficiency has been rapidly modified by population growth in some countries. The sustainability of traditional systems depended there heavily on the availability of new land and on soil fertility as well as on financing for food imports from non-agricultural sources. Apart from Colombia, El Salvador, Peru and Suriname, in 1960 the arable land *per caput* in Latin America was more than 0.25 ha/*caput* which keeps a large place for fallow and does not require high crop yields for achieving food self-sufficiency (Table 4).

In Peru, the use of fertilizers was initiated in the 1950s, but the economic development was not sufficient for the development of fertilizer use by small farmers and the arable land was largely expanded, even in marginal areas, thus maintaining the arable land *per caput* from 1960 to 1990 (41 kg/ha N, P_2O_5, K_2O). In Colombia, the decreasing availability of land was compensated as far as possible by the development of fertilizer use (101 kg/ha in 1990), while in El Salvador, where an early development of fertilizer use (104 kg/ha in 1960) was implemented, the arable land *per caput* decreased sharply without the compensation of an increase in fertilizer use. In Suriname, the available arable land *per caput* increased by 50% over 30 years and fertilizer use was maintained at a modest level during that period and even decreased significantly during the last 10 years. In Costa Rica, the availability of land became a serious constraint in the 1970s and the use of mineral fertilizers (100 kg/ha in 1960 mainly on coffee) developed rapidly (203 kg/ha in 1990). The same development, although less considerable, occurred in Guatemala (66 kg/ha in 1985) and in Mexico since 1975 (70 kg/ha in 1990). In Nicaragua, the civil unrest stopped the development of fertilizer use initiated in 1980 to make up for the scarcity of land (50 kg/ha in 1985). In Panama, the unfavourable economic situation has hampered the development of fertilizer use since 1975 (47 kg/ha). In Venezuela, the use of mineral fertilizer took off vigorously in 1975 and reached the level of 138 kg/ha in 1990 when the arable land *per caput* dropped below 0.33 ha. In Belize, the development of fertilizer use initiated in the late 1950s, but declined from 1975 to 1985. The serious scarcity of land has pressed for a new development and the average fertilizer dose was 88 kg/ha in 1990. In Chile and Ecuador, the development of fertilizer use is limited and occurred during the last ten years (69 kg/ha and 29 kg/ha) under the pressure of both decreasing arable land and the opening of new markets for export.

Apart from these situations calling for intensification, in other Latin American countries, since land is largely available, mineral fertilizers have been mostly used for cash crops in large farms (Brazil 43 kg/ha, Guyana 33 kg/ha, Uruguay 54 kg/ha). In Argentina and Paraguay, the wide availability of land favours very extensive practices and the use of mineral fertilizers is still very limited. In Bolivia, the extreme poverty of farmers in the Cordillera and the very extensive farming in the Amazon area are unfavourable conditions for the modification of the traditional mining agriculture.

In the Caribbean, the intensification of agriculture varies greatly from one island to another and even within the same island according to differences in farming systems and land tenure. In Cuba, the centralized economy has pressed for an intensive use of mineral fertilizers (199 kg/ha in 1990) to support sugar exports. In Haiti, in spite of the low availability of land, farmers still practise low-input and low-productivity agriculture with dangerous consequences for the environment. The availability of arable land was lower than

TABLE 5

Near East - share of total fertilizer used in irrigated areas and annual dose of fertilizer (1960 taken as base)

Country	1960		1965		1970		1975		1980		1985		1990	
	share of fert.	kg/ha	share of fert.	kg/ha	share of fert.	kg/ha	share of fert.	kg/ha	share of fert.	kg/ha	share of fert.	kg/ha	share of fert.	kg/ha
Cyprus	100	380	80	304	70	481	60	244	62	354	59	349	55	354
Iraq	100	0	100	2	100	10	100	22	100	58	100	67	100	85
Israel	100	56	100	93	100	130	100	153	100	189	100	289	100	241
Jordan	100	46	100	137	100	76	100	89	85	333	80	251	75	345
Kuwait	100	0	100	0	100	0	100	0	100	330	100	150	100	200
Lebanon	100	241	70	288	60	291	55	317	55	288	50	295	70	225
Oman	100	0	100	0	100	0	100	5	100	31	100	20	100	100
Qatar	100	0	100	0	100	0	100	0	100	300	100	166	100	220
Saudi Arabia	100	0	100	14	100	11	100	28	100	40	100	371	100	573
Syria	100	10	100	32	100	64	100	82	100	237	100	335	100	360
Turkey	100	12	100	69	75	186	65	203	50	294	43	291	40	304
UAE	100	0	100	0	100	0	100	48	100	152	100	108	100	162
Yemen	100	0	100	0	100	2	100	18	100	50	100	65	100	34
Algeria	100	249	100	225	80	301	60	384	55	456	55	331	55	352
Egypt	100	73	100	88	100	122	100	131	100	247	100	341	100	401
Libya	100	22	100	29	100	49	100	79	100	267	100	432	100	323
Morocco	100	29	100	44	100	101	80	149	70	183	63	199	50	250
Tunisia	100	81	90	226	70	300	70	280	70	269	70	252	70	273

0.15 ha *per caput* in some other islands in 1960. However, the fertile volcanic soils and the possibility of double cropping have maintained a sufficient production level for food crops while fertilizer use was largely developed on cash crops and some staple food crops (177 kg/ha in Barbados, 88 kg/ha in Jamaica and Trinidad in 1970).

Therefore, in Latin America and in the Caribbean, the scarcity of land has in some regions pressed the farmers to use external inputs. However, in most countries, fertilizers are applied to cash crops and the development of fertilizer use depends on international markets for the corresponding products.

DEVELOPMENT OF IRRIGATED AREAS AND OF MINERAL FERTILIZER USE IN THE NEAR EAST AND NORTH AFRICA SINCE 1960

In the countries of the Near East and North Africa, the shortage of rainfall is the main limiting factor for crop production. Therefore, most countries have developed irrigation as far as possible in order to compensate for the scarcity of arable land receiving sufficient rainfall for cropping. In the North African countries, the availability of rain and the share of the land receiving sufficient rainfall for rainfed agriculture is decreasing from West to East. However, during the last 30 years, irrigated areas have been increased by 50% in Morocco and Algeria, four times their size in Tunisia, and have doubled in Libya. Thus, irrigated land has reached 14.6% of the arable land in Morocco, 4.5% in Algeria, 5.6% in Tunisia and 11.5% in Libya. In the Mediterranean coast of the Near East, the development of irrigation facilities during the last 30 years has also been tremendous and deserves being analysed from North to South. In Turkey, the irrigated area was multiplied by 1.8, in Syria by 1.24, in Lebanon by 2.1, in Jordan by 2.0, in Israel by 1.53, in Cyprus by 1.17 and in Egypt by 1.02. In the Arab Peninsula, during the last 30 years, the irrigated area was multiplied by 2.04 in Iraq, by 2 in Kuwait, by 2.62 in Saudi Arabia, by 2.9 in Oman and by 1.5 in Yemen. Thus, in the Mediterranean area, the irrigated land in proportion to the total arable land reached the following levels in 1990: 8.4% in Turkey, 12.3% in Syria, 29% in Lebanon, 45.9% in Israel, 16.9% in Jordan and 99.5% in Egypt. In the Arab Peninsula, in 1990, the irrigated land, in proportion to the total arable land, reached 46.5% in Iraq, 73.2% in Saudi Arabia, 98% in Oman and 20.8% in Yemen. In Kuwait, Qatar and the United Arab Emirates, all cropped areas have always been irrigated, and irrigated areas have been increased four times during the last 30 years.

Since 1990, the expansion of arable land has been very limited, except in Iraq (+16.6%), Jordan (+27.4%) and Saudi Arabia (+86.4%). Therefore, farmers in Near East and North African countries rely heavily on rainfed cropping systems in Morocco, Algeria, Tunisia, Turkey and Syria, but the irrigated sector plays a major role in the development of crop production, except perhaps in Algeria. In Libya, Lebanon, Israel and Jordan, the rainfed sector is not providing the largest part of crop production, albeit still important. In all other countries, the irrigated areas provide most, or the total, of crop production.

The evolution of fertilizer use on irrigated areas is presented in Table 5 (1910-1990).

In North African countries, the development of the use of mineral fertilizers has been regular but rather limited since 1960. Due to the very large rainfed crop sector and the heavy climatic risks in most of the corresponding areas, the average fertilizer dose on arable land was very low in 1990. However, most fertilizers used in these countries have been supplied to irrigated areas. On the basis of the fertilizer use survey conducted by IFA, FAO and IFDC in 1986, it appears that the share of fertilizer used on irrigated areas, taking the 1960 level as 100%, fell, in 1990, to 50% in Morocco, 55% in Algeria and 70% in Tunisia but was maintained at 100% in Libya. On irrigated areas, the fertilizer dose per ha in Morocco, in 1990, was 250 kg, while it rose to 352 kg in Algeria, 273 kg in Tunisia and 323 kg in Libya. Even if the cropping intensity in irrigated areas is slightly over 1, the supply of mineral fertilizers is considered already high in those areas.

In the Mediterranean area of the Near East, the development of overall mineral fertilizer use since 1960 has been two-fold as that in North Africa. As, for example, consumption in 1990 was 142 kg/ha in Cyprus and 241 kg/ha in Israel, but it was limited to 64 kg/ha in Turkey. In Turkey, the share of the irrigated sector in fertilizer consumption is estimated to have decreased from 100% to 40% during the last 30 years, and the average fertilizer dose under irrigation in 1990 was 304 kg/ha. In Syria, nearly all fertilizers are used in irrigated areas, with an average supply of 360 kg/ha in 1990. The same situation occurs in Israel, with 241 kg/ha of fertilizers in irrigated areas in 1990. In Jordan and Lebanon, 70-75% of the fertilizers were supplied to irrigated areas in 1990, with 345 kg/ha and 225 kg/ha respectively. In Egypt, all fertilizers have always been applied to the irrigated areas, and the average dose in 1990 was 401 kg/ha.

In the Arab Peninsula, all fertilizers are supplied to the irrigated areas. In 1990, fertilizer use was very limited in Yemen (34 kg/ha), and relatively limited in Iraq (84.5 kg/ha) and Oman (100 kg/ha). It was quite significant in the United Arab Emirates (162 kg/ha), in Kuwait (200 kg/ha) and in Qatar (220 kg/ha). The average dose of fertilizers applied in irrigated areas in Saudi Arabia is very high (573 kg/ha).

Near Eastern countries are far more dependant than Asian countries on the use of mineral fertilizers for achieving the level of agricultural production fixed by agricultural plans. In Northern Africa and in the northern Mediterranean areas of the Near East, the rainfed sector is still very important and little intensified. Therefore, the high cost of irrigation has to be recovered from the highest possible productivity of the land. Improving the productivity of plant nutrients and monitoring the combination of water and plant nutrient supply for more sustainable agriculture is a major challenge in this area, in which fertigation could play a role.

DECREASING AVAILABILITY OF ARABLE LAND IN AFRICA AND THE VERY LOW DEVELOPMENT OF THE USE OF EXTERNAL INPUTS

In the Sahelian countries of Western Africa, the arable land *per caput* is decreasing very rapidly. In 1990, in Chad, the available land *per caput* was still sufficient (0.60 ha). In Senegal the geographic distribution of population aggravated the availability of land, while the average value still favoured extensive agriculture in 1990 (0.76 ha). In Niger, the pressure on arable land is now problematic (0.46 ha/*caput*). In Mali and in the Gambia, land is relatively scarce (0.23 and 0.20 ha/*caput*). In Mauritania with 0.09 ha arable land *per caput*, the country depends heavily on food imports. In all these countries, fertilizer use in 1990 was lower than 10 kg/ha and had very limited impact on crop production.

In the Sudano-Sahelian countries of Western Africa, the situation is more favourable, even if the future is problematic as well. In 1990, there were still 0.41 ha of arable land *per caput* in Benin and Togo, 0.37 ha in Burkina Faso, 0.35 ha in Guinea Bissau and 0.33 ha in Côte d'Ivoire. The situation is really difficult in Ghana with 0.20 ha arable land *per caput*. However, the initiation of fertilizer use has only been implemented in Côte d'Ivoire and Togo, and fertilizers are mostly applied to cash crops (sugar cane, cotton, coffee).

In the dry countries of Eastern Africa, the availability of arable land was still very large in 1990 in Botswana (1.08 ha) and quite large in Namibia (0.38 ha) and Sudan (0.50 ha). Mineral fertilizers are only used in irrigated areas of Sudan. In Somalia, the availability of land is close to 0.14 ha today and without fertilizer use the country cannot be self-sufficient. In Kenya, where only 0.10 ha of arable land *per caput* were available in 1990, the development of fertilizer use (46 kg/ha) maintains a fragile and unsatisfactory food self-sufficiency level, while in Ethiopia, with 0.29 ha *per caput* and no fertilizer use, the shortage of food is chronic. In Mozambique (0.26 ha/*caput*), the very low use of mineral fertilizers has created a very difficult situation. In Zimbabwe, where the availability of arable land is close to that of Mozambique, the use of 60 kg/ha of fertilizer on 0.29 ha of arable land *per caput* has maintained a surplus production of maize.

In Central Africa and on the western slopes of Fouta Djallon, population densities create contrasts between the countries located in the same type of ecological conditions. In the Eastern Highlands, countries having two cropping seasons per year presented, in 1990, a very low availability of arable land *per caput*: Uganda 0.37 ha, Burundi 0.25 ha, Lesotho 0.23 ha, Rwanda 0.17 ha. Significant fertilizer use has been initiated in Lesotho, which has been stagnant since 1980 (11 kg/ha). In the same region, the range of available arable land *per caput* decreased from the driest to the more rainy countries in 1990: Zambia 0.62 ha; Malawi 0.28 ha; Swaziland 0.25 ha; Tanzania 0.19 ha. Fertilizer use took off in Swaziland in the 1970s, but the consumption dropped from 108 kg/ha in 1980 to 39 kg/ha in 1990. Malawi recently promoted the use of fertilizers (20 kg/ha), while the consumption is still very limited in Zambia (11 kg/ha) and Tanzania (9 kg/ha). In the humid savannahs and forests of the western slopes of Fouta Djallon, the land was largely available in Sierra Leone in 1990 (0.50 ha/*caput*), while the scarcity of land is ascertained in Guinea (0.15 ha) and Liberia (0.15 ha) in spite of two cropping seasons per year. There is no consumption of fertilizers in these three countries. In Central Africa, the land was largely available in 1990 (0.69 ha/*caput*), in Cameroon (0.63 ha), in Gabon (0.60 ha), in Angola (0.36 ha) and mineral fertilizer consumption is limited to cash crops (cotton, sugar cane). The availability of land is more restricted in Nigeria and Zaire (0.23 ha), and fertilizer use is limited to cash crops and to the savannahs of Nigeria, where the pressure on the land is considerable. The availability of land is still very limited and cash crops are mainly cultivated. This country depends heavily on food imports.

In conclusion, apart from the dry southern countries, the western slopes of Fouta Djalon and the central African countries, the scarcity of land is now a very limiting factor for the sustainability of traditional extensive cropping systems (Table 6). Mineral fertilizer consumption is not developed in most countries, which may be caused by a relative availability of land and the lack of agricultural product markets. However, most traditional practices in quite densely populated areas are severely mining the plant nutrient reserves of the soil and are threatening the future production capacity of many countries.

TABLE 6

AFRICA: Evolution of arable land, population and fertilizer use (N + P_2O_5 + K_2O)

	Fertilizer use (metric tons)		Arable land ('000 ha)		Fertilizers (kg/ha)		Population ('000)		Fertilizers (kg/caput)	
	1980	1990	1980	1990	1980	1990	1980	1990	1980	1990
Angola	16 800	9 500	3 500	3 600	4.80	2.60	7 723	10 020	2.18	0.95
Benin	862	7 100	1 795	1 880	0.50	3.80	3 459	4 630	0.25	1.53
Botswana	1 400	900	1 360	1 400	1.00	0.60	902	1 304	1.55	0.69
Burkina Faso	4 308	14 000	2 785	3 325	1.50	4.20	6 957	8 996	0.62	1.56
Burundi	1 100	2 100	1 309	1 345	0.80	1.60	4 132	5 472	0.27	0.38
Cameroon	32 024	21 800	6 930	7 430	4.60	2.90	8 653	11 823	3.70	1.84
Central Africa	1 454	900	1 945	2 090	0.70	0.40	2 320	3 039	0.63	0.30
Chad	900	5 800	3 150	3 400	0.30	1.70	4 477	5 678	0.20	1.02
Comoros	0	0	91	98	0.00	0.00	392	550	0.00	0.00
Congo	512	2 000	148	176	3.50	11.40	1 669	2 271	0.31	0.88
Côte d'Ivoire	53 100	35 700	3 095	3 895	17.20	9.20	8 194	11 997	6.48	2.98
Ethiopia	43 200	111 800	13 880	14 200	3.10	7.90	38 750	49 240	1.11	2.27
Gabon	100	1 121	452	700	0.20	1.60	806	1 172	0.12	0.96
Gambia	2 025	600	156	170	13.00	3.50	641	861	3.16	0.70
Ghana	12 000	13 000	2 760	2 880	4.30	4.50	10 736	15 028	1.12	0.87
Guinea	280	500	702	750	0.40	0.70	4 461	5 755	0.06	0.09
Guinea-Bissau	210	586	285	335	0.70	1.70	795	964	0.26	0.61
Kenya	61 600	116 000	2 270	2 480	27.10	46.80	16 632	24 031	3.70	4.83
Lesotho	4 500	4 600	392	407	11.50	11.30	1 339	1 774	3.36	2.59
Liberia	3 107	3 000	371	380	8.40	0.80	1 876	2 575	1.66	0.12
Madagascar	8 800	8 111	3 000	3 100	2.90	2.60	8 785	12 004	1.00	0.68
Malawi	33 264	48 000	2 320	2 440	14.30	19.70	6 183	8 754	5.38	5.48
Mali	14 194	15 200	2 050	2 120	6.90	7.20	6 863	9 214	2.07	1.65
Mauritania	1 300	1 900	195	190	6.70	10.00	1 551	2 024	0.84	0.94
Mauritius	26 661	27 733	107	108	249.00	257.00	966	1 082	27.60	25.60
Mozambique	27 600	2 600	3 080	4 050	9.00	0.60	12 095	15 656	2.28	0.17
Namibia	0	0	657	670	0.00	0.00	1 306	1 781	0.00	0.00
Niger	2 693	1 021	3 552	3 600	0.80	0.30	5 586	7 731	0.48	0.13
Nigeria	173 900	400 340	30 385	31 300	5.70	12.80	78 430	108 542	2.22	3.69
Rwanda	100	2 889	1 015	1 220	0.10	2.40	5 163	7 237	0.02	0.40
Senegal	19 400	11 750	5 225	5 500	3.70	2.10	5 536	7 327	3.50	1.60
Sierra Leone	1 792	1 300	1 766	2 100	1.00	0.60	3 263	4 151	0.55	0.31
Somalia	1 200	2 700	1 000	1 060	1.20	2.50	5 345	7 497	0.22	0.36
Sudan	80 700	80 889	12 420	12 700	6.50	6.40	18 681	25 203	4.32	3.21
Swaziland	20 323	7 500	189	195	107.50	38.50	563	788	36.10	9.52
Tanzania	35 500	48 400	5 160	5 320	6.90	9.10	18 867	27 318	1.88	1.77
Togo	2 653	11 500	1 420	1 440	1.90	8.00	2 615	3 531	1.01	3.26
Uganda	800	192	5 680	6 900	0.10	0.03	13 120	18 794	0.06	0.01
Zaire	7 900	6 200	7 600	8 050	1.04	0.80	26 225	35 568	0.30	0.17
Zambia	78 600	59 600	5 108	5 260	15.40	11.30	5 738	8 452	13.70	7.05
Zimbabwe	173 462	170 534	2 539	2 835	68.30	60.20	7 126	9 709	24.34	17.56
Total Africa	950 324	1 256 666	141 840	151 099	6.70	8.30	358 921	489 543	2.65	2.57

EVALUATION OF REQUIREMENTS FOR PRODUCTIVITY OF CROPPING SYSTEMS DURING THE NEXT 20 YEARS AND CONSEQUENCES FOR PLANT NUTRIENT MANAGEMENT

Population growth has been a dominant feature of the developing countries for the last 40 years, invalidating a part of the efforts for their economic development. Population will increase by more than 30% during the next ten years in 52 countries and by more than 20% in 72 countries over the same period. The rapid growth of population is of particular concern in 90% of the sub-Saharan African countries. As indicated in the previous pages, the arable land *per caput* is decreasing in the large majority of the developing countries. The reduction of fallow and the development of double cropping have in many countries limited the need for a substantial improvement of crop yields in order to face the requirements of the burgeoning population. However, in other countries, and specially in Europe and in Asia, the scarcity of land and the development of markets for surpluses have led to important increases in crop yields.

When the cropped land area increases and when crop yields increase, the demand for plant nutrients in the cropped area also increases. Within the territory of a village or within the land of each farm, the mobilization of natural sources of plant nutrients has been spurred on. The renewable resources (N fixation, K supply from irrigation water) may be further mobilized up to a certain extent through crop rotation and cultivation practices. Natural supply of N, P_2O_5 and K_2O from rain, dust and natural weathering of soils may be further mobilized on the total land of an area and concentrated on the cropped areas through more efficient farming techniques. However, the intensification of the use of the land has in most cases dramatically augmented the losses of plant nutrients through erosion, volatilization and leaching, and has definitely increased exports of plant nutrients. Thus, in addition to the renewable sources of plant nutrients, the non-renewable capital of plant nutrients is already being partially consumed by farmers. The supply of mineral fertilizers may efficiently contribute to limiting the consumption of the non-renewable capital of plant nutrients, to equilibrating the ratios between the various nutrients and to adjusting the supply of nutrients to the demand for targeted crop yields. However, mineral fertilizers should not in the first instance be used to compensate for insufficiently controlled losses of plant nutrients provoked by unadapted land use and cultivation practices.

As shown in Figures 3 to 13, fertilizers have been used in European as well as Asian countries, when the available arable land approached a threshold related to ecological conditions and to the market conditions for export of agricultural products (Tables 7 and 8). In Western Europe, the threshold value was in the order of 0.25 ha *per caput* in Austria and Federal Germany just after the second world war. This threshold value was in the order of 0.20 ha for the United Kingdom, Belgium and The Netherlands. In Switzerland, largely oriented towards livestock production through natural pastures, the threshold value was in the order of 0.15 ha of arable land *per caput*. In North Asia, the threshold value in China and Nepal has been 0.14 ha arable land *per caput*, while in the Democratic People's Republic of Korea it was close to 0.22 ha. In India and Pakistan the threshold value is close to 0.26 ha. In the Northern part of South Asia, the threshold value was 0.12 ha arable land *per caput* in Bangladesh, 0.14 ha in Indonesia, 0.17 ha in Viet Nam, 0.18 ha in the Philippines and 0.19 ha in Sri Lanka. It is worth noting that the countries oriented towards agricultural exports have developed fertilizer use well before attaining the threshold value of arable land *per caput*, thus inducing the take-off of fertilizer use in their ecological situation. It is observed

TABLE 7

EUROPE – Fertilizers (N + P_2O_5 + K_2O) kg/ha

Country	1950	1055	1960	1965	1970	1975	1980	1985	1990
Albania	0	0	0	12.8	64.7	96.5	139.7	132.2	150.6
Austria	26.5	51.1	116.2	197.8	242.1	224.0	262.3	269.6	215.8
Belgium + Lux.	262.3	311.3	341.4	439.3	564.4	581.9	528.1	513.0	503.7
Bulgaria	4.6	17.0	22.9	62.2	152.9	130.6	196.4	226.7	194.1
Czechoslovakia	34.2	58.8	94.7	152.7	222.8	295.7	337.6	339.5	322.1
Denmark	95.8	114.1	161.3	176.0	216.6	215.9	263.0	252.2	248.7
Finland	49.3	57.7	77.4	117.1	170.6	224.1	191.1	210.7	211.6
France	50.4	67.4	91.8	149.7	218.2	245.6	312.5	300.4	304.5
Germany FR	167.3	210.5	278.1	335.9	379.1	428.9	479.8	525.6	387.5
Germany DR	131.2	144.1	187.9	256.1	312.2	372.8	340.2	310.9	349.1
Greece	13.8	25.1	34.9	63.9	88.6	112.8	148.0	167.8	174.8
Hungary	8.5	0	33.4	60.8	124.9	243.2	281.6	287.9	246.3
Ireland	53.5	85.8	114.2	192.5	328.1	291.3	(533.6)	(656.5)	(730.1)
Italy	27.1	36.0	54.4	61.6	82.5	103.3	189.3	172.6	150.0
Malta	0	0	20.8	28.0	35.9	26.2	44.7	66.1	39.4
Netherlands	390.4	422.9	457.7	575.0	710.6	358.7	806.8	807.1	645.2
Norway	139.0	146.6	168.2	194.2	241.5	293.4	327.2	293.4	245.9
Poland	22.1	33.5	52.6	70.6	157.7	229.2	242.9	221.0	205.6
Portugal	24.6	33.6	37.2	45.5	53.7	68.1	87.6	68.6	86.4
Romania	0	0	6.2	17.9	51.2	67.7	136.3	141.8	197.3
Spain	14.2	23.6	28.8	37.3	58.7	71.6	82.2	80.3	101.0
Sweden	56.9	69.9	83.9	119.6	155.0	161.1	170.2	156.2	128.3
Switzerland	113.7	160.3	224.9	310.4	360.6	367.6	448.4	436.7	426.2
UK	111.4	118.6	176.0	200.3	221.8	242.1	319.5	366.8	354.4
Yugoslavia	2.4	0	33.0	56.6	71.1	84.6	110.4	125.4	115.9
Total	44.72	56.85	83.14	112.6	158.63	192.42	232.28	228.27	221.23

TABLE 8

EUROPE – Arable land/*caput*(ha)

Country	1950	1055	1960	1965	1970	1975	1980	1985	1990
Albania	0.294	0.253	0.292	0.269	0.261	0.273	0.263	0.240	0.218
Austria	0.268	0.254	0.249	0.232	0.227	0.199	0.203	0.192	0.185
Belgium + Lux.	0.125	0.117	0.108	0.100	0.094	0.088	0.081	0.080	0.079
Bulgaria	0.592	0.568	0.568	0.556	0.533	0.498	0.471	0.461	0.462
Czechoslovakia	0.447	0.421	0.397	0.379	0.369	0.355	0.338	0.332	0.325
Denmark	0.633	0.614	0.608	0.568	0.544	0.526	0.518	0.511	0.500
Finland	0.610	0.608	0.600	0.597	0.580	0.561	0.536	0.492	0.489
France	0.505	0.492	0.472	0.420	0.379	0.360	0.351	0.349	0.341
Germany FR	0.179	0.173	0.154	0.145	0.136	0.122	0.122	0.122	0.120
Germany DR	0.281	0.283	0.294	0.312	0.297	0.293	0.301	0.299	0.303
Greece	0.437	0.441	0.444	0.451	0.408	0.427	0.407	0.397	0.392
Hungary	0.620	0.589	0.570	0.556	0.543	0.521	0.498	0.500	0.510
Iceland	0.035	0.032	0.028	0.026	0.024	0.037	0.035	0.033	0.031
Ireland	0.434	0.423	0.486	0.399	0.391	0.389	0.462	0.292	0.269
Italy	0.356	0.328	0.321	0.289	0.278	0.228	0.220	0.212	0.210
Malta	0.054	0.061	0.058	0.050	0.049	0.040	0.036	0.038	0.037
Netherlands	0.105	0.097	0.091	0.071	0.067	0.062	0.060	0.060	0.062
Norway	0.249	0.241	0.235	0.219	0.210	0.198	0.200	0.207	0.204
Poland	0.674	0.595	0.546	0.487	0.467	0.444	0.421	0.399	0.387
Portugal	0.378	0.443	0.463	0.410	0.391	0.343	0.322	0.311	0.309
Romania	0.578	0.547	0.562	0.552	0.519	0.494	0.473	0.467	0.433
Spain	0.678	0.662	0.681	0.652	0.619	0.585	0.546	0.529	0.519
Sweden	0.535	0.519	0.481	0.395	0.379	0.367	0.358	0.350	0.330
Switzerland	0.104	0.090	0.082	0.068	0.064	0.062	0.065	0.064	0.061
UK	0.146	0.139	0.139	0.134	0.130	0.123	0.124	0.124	0.116
Yugoslavia	0.481	0.463	0.456	0.421	0.400	0.276	0.353	0.336	0.325
Total	0.375	0.367	0.358	0.342	0.318	0.300	0.291	0.285	0.277

that farmers who are mainly oriented towards self-consumption of their agricultural products are using the land as extensively as possible, with high risks of mining non-renewable reserves. The use of external inputs will then not be promoted before the threshold value of arable land *per caput* is reached.

Modelling is a useful tool for the evaluation of the possible situation of land use by the year 2000 and 2010. It assists in identifying the crop productivity requirements at country level within a given set of hypotheses. One scenario could result from the following assumptions until 2010: (i) within the assessed availability of land, the total arable land increases proportionally to recent expansion; (ii) the area with industrial crops increases by 20% every 10 years; (iii) as far as possible, the area cropped with annual crops increases in proportion with the total population; and (iv) the share of the various food crops is not modified within the food cropped area. Thus, through slight intensification, the revenues from cash crops are roughly maintained, if their value on the market is maintained during the period. The cropped area then presents the maximum possible expansion.

On the basis of these assessments, fallow will virtually have disappeared by 2010 in 17 out of 20 Asian countries (only Afghanistan, Cambodia, Laos, Mongolia and Viet Nam will have fallow). In sub-Saharan Africa, there will be no more fallow in 20 countries out of 41, and in 29 countries there will be less than 25% of the land available for annual crops under fallow. In Latin America and the Caribbean, possibilities for fallow will have disappeared in five countries and will be lower than 25% in nine countries out of 27. However, most small farmers will probably not have any fallow left; it will be concentrated in large farms. In the Near East, only farmers in Algeria, Libya and Tunisia will have fallow. Putting the land under fallow is a method for harvesting naturally-supplied plant nutrients and for extracting the nutrients from the subsoil. The nutrients thus collected are available for crops following the fallow. However, this important source of plant nutrients will soon end for most farmers in developing countries. Natural supply from rain and dust is estimated in the range of 5 to 15 kg of plant nutrients per ha. Nitrogen fixation and supply of nutrients from the subsoil through the fallow are estimated in the range of 15 to 45 kg/ha/year. Short-term fallow has no significant impact on plant nutrient availability if less frequent than once every three cropping seasons. However, the development of leguminous cash crops and other industrial annual crops could create better conditions for crop rotation, nitrogen biofixation and use of available plant nutrients. Land for green manure growing along a full cropping season will not be available for the large majority of farmers. In most cases, green manure should be intercropped.

If food self-sufficiency in Asia is to be improved, food crop yields will need to reach quite a high level in most countries by 2010. In most countries of northern Asia, average yields should reach 1.5 t/ha for wheat and more than 3 t/ha for paddy rice. In China, average cereal yields should be over 5.4 t/ha, and in the two Republics of Korea they should be close to 8 t/ha. In South Asia, the required average paddy yields will be 3.7 t/ha for countries with a medium population density, such as the Philippines, and 6.7 t/ha for heavily populated countries, like Bangladesh.

By 2010, in the countries of Latin America with limited rainfall, maize yields should be close to, or over, 2.5 t/ha (e.g. in Bolivia), while in Mexico average maize yields should exceed 3.5 t/ha. In the countries exporting wheat, average yields should be over 3 t/ha (e.g. in Argentina). For the humid countries, average maize yields should be over 2 t/ha in Haiti

TABLE 9

Examples of export of plant nutrients (kg/ha) by crops within possible intensification through maximum development of cropped areas

Country	Crop	Export. prods.	1990					2010				
			Yield kg/ha	N	P_2O_5	K_2O	Total	Yield kg/ha	N	P_2O_5	K_2O	Total
Senegal	Millet	Grain	600	12	3.6	3	18.6	730	15	5.0	4	24
		Straw	1700	12	2.4	38	52.4	2070	15	3.5	51	69.5
		Total		24	6	41	71.0		30	8.5	55	93.5
Togo	Sorghum	Grain	650	8.5	4.0	2.5	15	840	12	5.0	2.2	19.2
		Straw	3350	6	2.3	17	25.3	4350	8.5	3.4	23.5	35.4
		Total		14.5	6.3	19.5	40.3		20.5	8.4	25.7	54.6
Pakistan	Wheat	Grain	1800	29	10	39.5	78.5	2700	44	16	59	119
		Straw	2340	24	4	88.5	116.5	3380	35	6.5	148.5	190
		Total		53	14	128	195		79	22.5	207.5	309
Philippines	Rice	Grain	2800	31	15	10	56	4630	65	30	20	115
		Straw	3500	54	12	104	170	5700	80	20	200	300
		Total		85	27	114	226		145	50	220	415
Nicaragua	Maize	Grain	1100	16	5.5	6.5	28	1580	24	8	10	42
		Straw	1460	14	2.5	17.5	34	2100	17	3	38	58
		Total		30	8	24	62		41	11	48	100
Bolivia	Potato	Tubers	6800	14	2	23	39	10300	40	14.5	50.5	105
		Residues	1700	26	9.5	33.5	68	2580	36	6	84	116
		Total		40	11.5	56.5	107		66	20.5	134.5	221

and Honduras, 2.5 t/ha in Brazil, and 3 t/ha – and frequently over 3.5 t/ha – in most other countries.

By 2010, in Africa, due to a diet that is lower than in most countries of other continents and on account of the relative availability of land, the required yields will be below those shown by the former figures. Nevertheless, a substantial growth of cereal and tuber yields is required. The driest countries (Botswana, Chad, Niger) should reach 0.8 t/ha of cereal grains, while other Sahelian countries should obtain a minimum cereal yield of 1.1 t/ha. Within the Horn of Africa, cereal yields should reach 1.6 t/ha. Most African countries of the humid savannah zone should produce at least 1.7 t/ha of cereals (like Rwanda or Ethiopia), while some of them, like Nigeria, Madagascar and Congo, should obtain 2.0 to 2.2 t/ha of cereals. An exceptional development of cereal yields is required in Kenya (2.4 t/ha), Tanzania (2.7 t/ha) and Ghana (3 t/ha).

The required yields in developing countries by the year 2000, and particularly by 2010, imply a significant increase of the mass of plant nutrients involved in the farming systems (Table 9), as a result of both the required increase of yield (multiplication by an average of 1.5) and of the increase in amount of cropped area in the countries (multiplication by an average of 1.3). The resulting increase in the amount of the plant nutrient exported by food crops in 20 years' time can be estimated at 195% with a variation estimated at 160-200%. In order to secure or improve food security from domestic production, the average annual growth rate of the amount of plant nutrients within the biomass of food crops should be 3.5%, ranging from 2.2% for the countries with a favourable food supply and land availability in 1990, to 4.3% for the countries in the most difficult situation.

Recycling of crop residues may theoretically provide 40 to 50% of the exports of nitrogen by the crop, 25 to 40% of the exports of phosphorus and 70% of the exports of potash if no losses occur during the recycling process. When the crop residues are ploughed in, supplied phosphorus is preserved, but more than 20% of nitrogen and 30% of supplied potash are lost (volatilization and leaching) in many ecological systems. Transformation of crop residues into manure strongly reduces the bulk of residues, but it causes heavy losses of plant nutrients through the combination of the following mechanisms: (i) only 90% of the nutrients supplied in fodder are excreted by the animals; (ii) when the residues are grazed, only two-thirds of the excreta, at the maximum, are available for manure; (iii) only 50 to 75% of the nutrients from the excreta are really available in the manure actually spread on the fields. Thus, through manuring, less than 70% of the plant nutrients recycled from residues on the farm may be available for crops. With cereals, it is estimated that a maximum of 35% of the total uptake of nitrogen, 30% of the phosphorus and 60% of the potash are recycled through crop residues.

Leguminous crops fix nitrogen. However, when the grains are harvested, leguminous crops provide less than 20 kg/ha of N in semi-arid tropics (groundnuts) and 40 kg/ha of N in humid tropics (soybean). Such a level of N fixation requires high availability of phosphorus. The restitution of the residues of leguminous crops provides additional nitrogen, within the same range as cereal residues. However, the share of leguminous crops in annual food cropped areas is limited: 25-30% in India, Myanmar and the Democratic Republic of Korea: 15-18% in China, Indonesia and Pakistan, and less than 8% in other Asian countries; 20% in Brazil and less than 12% in other Latin American countries; 20-25% in Burkina Faso, Niger, Senegal, Malawi, Kenya (mainly groundnuts), Burundi, Rwanda, Tanzania, Uganda (mainly beans with low N-fixing capacity), and less than 10% in other African countries. Thus, in average conditions and in the more favourable situations, leguminous crops will provide fixed nitrogen for three crops in the rotation, while in the less favourable situations, leguminous crops will rotate with more than nine other crops. The "average nitrogen supply" from leguminous crops to other crops may be evaluated at 14 kg/ha/crop in intensive soybean/cereal agriculture if one soybean crop is grown every four crops, and at 5 kg/ha when soybean crops are less frequent; this supply may be evaluated at 7 kg/ha in rather intensive groundnut/cereal agriculture with one groundnut crop per every four crops. The nitrogen supply from beans is very limited. The relative increase of 20% of the share of leguminous crops in the annually cropped area before 2010, assessed as an hypothesis above, would result in a significant increase of fixed N available to the crops.

Transfers of plant nutrients from non-cropped to cropped areas by livestock is an important source of plant nutrients for the farmers having livestock and considerable non-cropped areas producing fodder. However, this transfer should not exceed the natural replenishment of the plant nutrient stock available in non-cropped areas (12 to 25 kg/ha), otherwise these reserves would be mined. In fact, in many countries, farmers are every year transferring an excessive part of the plant nutrients stored in the natural vegetation and in the non-cultivated soil, thus ruining a non-renewable capital of nutrients. A minimum of 4 to 5 ha per adult cow is required for fodder production in humid tropics, and in many semi-arid tropics 7 to 10 ha are needed. An adult cow (350 kg) produces 3 tons of dung, of which 2 tons that are dropped during grazing may be used for manuring. Therefore, the supply of 10 t/ha of manure requires 5 cows for 1 ha of crop land and between 20 and 50 ha of non-cropped land. If the manure is supplied once every four years, the ratio needed between the cropped area receiving manure and the non-cropped area providing the manure is 5/1 or 12/1. In fact, very few farmers in developing countries have access to sufficient non-cropped areas for the production of manure which could meet the requirements for plant nutrients of the whole cropped area, even with 10 t/ha of manure supplied every four years. Quite accurate evaluations of the areas receiving manure have been made in some village territories (African Savannah – Fertile Soils, International Seminar, Montpellier 1990), from which the contribution of non-cropped areas has been evaluated. It appeared that in semi-arid tropics, less than 6% of the cropped areas receive an average dose of 10 t/ha of manure every year, while in humid tropics and with buffaloes, up to 12% of the cropped area may be manured at this level. It is estimated that in most villages such manuring does not affect more than 5% of the cropped area each year. In good conditions, 1 ton of cow dung contains 8 kg N, 4 kg P_2O_5, and 16 kg K_2O. The transfer of plant nutrients from non-cropped to cropped areas may thus be evaluated at an average supply of ($4.8\ N + 2.4\ P_2O_5 + 9.6\ K_2O$) kg/ha every year on the total cropped area in semi-arid tropics, and of ($9.6\ N + 4.8\ P_2O_5 + 19.2\ K_2O$) kg/ha every year on the total cropped area in humid tropics with buffaloes.

In summary, the addition of plant nutrient from various local sources (fallow, crop residues, N fixation, transfer from non-cropped areas, rain and dust) does not totally cover the evaluated uptake by crops in the countries using no external sources of plant nutrients for food crops, especially for potash. This indicates clearly that the availability of plant nutrients is one of the major limiting factors for yields in these countries and that the soil is slowly mined of its plant nutrient reserves. In most Asian and Latin American countries, the present theoretically available plant nutrients from local sources do not represent more than 50 to 55% of the exports by the crops, and external sources of nutrients are to be used for compensation of the plant nutrient balance. Even with the maximum utilization of suitable virgin land, which lowers the required crop yields to the minimum, **it is impossible to meet the requirements of plant nutrients** for the targeted yields by 2010 **with the local plant nutrient sources quoted above and with the present use of mineral fertilizers** in almost all developing countries. If the crop yields are increased, the recycling process will theoretically increase proportionally. But the transfer of plant nutrients from non-cropped areas and the nitrogen fixation by leguminous crops cannot provide the required additional plant nutrients needed for the support of the cropping systems resulting from the growth of the cropped area.

Moreover, not all of the plant nutrients supplied are available for the crops. Major losses occur through volatilization, denitrification, leaching, runoff and immobilization. Therefore, the supply should be higher than the requirements, especially when the losses are not properly controlled. The various available plant nutrient sources do not have the same efficiency for plant nutrient supply to the crops. Accurate balance sheets of plant nutrients should be established in the various cropping systems and plant nutrition schemes in order to define the efficiency of plant nutrients. The intensification of plant nutrient management, aiming at an increase of crop yields and a better efficiency of plant nutrition practices, will result both from an increased supply of plant nutrients to the crops and from a better association of the various sources of plant nutrients. The combination of those sources and the overall level of plant nutrient supply depend heavily on the targeted yields, on the ecological conditions and on the economical and socio-economical conditions of the farmers. On this issue, the blanket recommendations have no interest. Applied agricultural research and extension should think in terms of identified conditions of production and production targets and should make available alternatives accordingly.

CONCLUSIONS: GUIDELINES FOR THE FORMULATION OF A PROGRAMME FOR THE PROMOTION OF INTEGRATED PLANT NUTRITION SYSTEMS SUPPORTING RURAL DEVELOPMENT

The objective of Integrated Plant Nutrition Systems (IPNS) is the rationalization of plant nutrition management in order to upgrade the efficiency of the plant nutrient supply and the farmers' income through the adequate association of local and external sources of plant nutrients accessible to the farmers. IPNS are evolving, as from the present situation the plant nutrient gains from better management are reinvested in the plant nutrient cycles in order to gradually increase the plant nutrient capital available on the farm: soil reserves, crop residues and manures, and cash flow for the purchase of mineral fertilizers. IPNS assume an initial diagnosis of plant nutrient management, the design of a plan for upgrading of the efficiency of plant nutrition, a decision on the use of the benefits from the investment agreed upon for the purchase of external sources of plant nutrients. The improvement of the control of plant nutrient losses is a crucial issue, but the labour costs and labour productivity improvements arising from the innovations are of special interest to the farmer. IPNS cannot be restricted to the saving of some nutrients units through the recycling of crop residues and manures. IPNS are not the promotion of any particular level of plant nutrients supply versus present practices. IPNS should promote efficient development of crop production according to the local requirements and the local cropping conditions.

Plant nutrient management cannot be addressed only at the scale of cropping systems and fields. The availability of the various plant nutrient sources within small rural regions should be assessed. A minimum modelling effort should analyse the sustainability of various alternatives for the use of local and external sources. The data should be obtained through networks of representative reference farms indicating the present efficiency of plant nutrients. Pilot farms should be testing the alternatives in such a way that the information thus generated may be used by the models assessing the sustainability of the innovations at the regional level. On the basis of economic interpretation of the results, and on condition that that the various plant nutrients are available in sufficient quantities, strategies for plant nutrition development should be elaborated by country, and possibly in each agricultural region, on the basis of site-specific documentation. Increasing the efficiency of plant nutrient management is a major objective for the development of sustainable agriculture.

IPNS should definitely be oriented towards rural development and sustainable agriculture. Thus, the development of the production capacity through the optimal use of the capital of plant nutrients available on farms, through the improvement of the productivity of this capital and through the annual supply of external inputs, is an important issue of this programme. The participation of farmers in identifying relevant technical innovations, efficient organizations and the sustainable use of natural resources is a crucial component of field programmes. This pragmatic approach promotes IPNS adapted to the social and economic conditions of the farmers, to their production goals and to the national requirements of agricultural development.

Integrated plant nutrition systems – basic concepts, development and results of trial network, initiation of project activities in AGLN and need for cooperation

Among the main results of the United Nations Conference on Environment and Development (UNCED), held in Rio de Janeiro in June 1993, was Agenda 21, a comprehensive plan of action on environment and development for the period 1993-2000. It consists of forty chapters and 115 programme areas, calling for a wide range of action at local, national, regional and international levels.

While many of the programme areas of Agenda 21 are relevant to FAO, Chapter 14 on promoting Sustainable Agricultural and Rural Development (SARD) is of special importance. The active involvement of FAO in the preparation of this chapter resulted in a large degree of convergence with FAO programme objectives. One of the eleven programme areas of Chapter 14 is Sustainable Plant Nutrition, with specific objectives as described below:

- not later than the year 2000, to develop and maintain in all countries the integrated plant nutrition approach, and to optimize availability of fertilizer and other plant nutrient sources;
- not later than the year 2000, to establish and maintain institutional and human infrastructure to enhance effective decision making on soil productivity;
- to develop and make available national and international know-how to farmers, extension agents, planners and policy-makers on environmentally sound new and existing technologies and soil-fertility management strategies for application in promoting sustainable agriculture.

SUSTAINABLE PLANT NUTRITION

As defined by FAO, sustainable agricultural development is the management and conservation of the natural resource base, and the orientation of technological and institutional change in such a manner as to ensure the attainment and continued satisfaction of human needs for present and future generations. Such sustainable development conserves or increases land capacity to

PAPER 1.2

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produce agricultural goods, water availability, plant genetic resources, is environmentally non-degrading, technically appropriate, economically viable and socially acceptable, in the medium term.

Clearly, agriculture and its development are far from sustainable in many parts of the world, both in developed and in developing countries. Pollution, very high rates of energy use and consumption of non-renewable resources need to be addressed in farming systems of many industrial parts of the world. Traditional agricultural management in many developing countries is threatened by the increasing population at rates higher than 2% per year, especially if plant nutrients exported from the fields or from community territories exceed the natural replenishment of soils by these nutrients (dry deposits and rain deposits, mineral weathering, irrigation water, nitrogen fixation) and applied nutrients from outside the same fields or the same territory. In most developing countries, for the next 50-100 years, agricultural production will need to be increased by at least 3% per year to maintain and improve nutrition and health and to enhance the self-reliance of resource-poor land users. This situation will drastically increase the exportation of plant nutrients from the fields, and from the whole community territory where farmers transfer plant nutrients from non-cultivated areas to their fields. The most important issue of our time is how to increase world agricultural production in the right places, while at the same time preserving the quality of the environment and the productive capacity of land and water resources.

An agricultural ecosystem differs from a natural one in that plant nutrients are constantly being removed. A natural ecosystem will generally be close to equilibrium in terms of plant nutrients and soil organic matter content; nutrients taken up by plants will eventually return to the soil in plant and animal residues and be recycled through the activities of soil fauna and micro-organisms. There will be little net output of nutrients between natural supply and losses (leaching and runoff). In an agricultural system this will very rarely be so as the aim is to produce plant material that is removed from the land for food or other uses. So there is, almost inevitably, a net removal of plant nutrients. At the very minimum, the quantity of nutrients removed in produce, plus those lost in other ways (e.g. leaching, runoff, gaseous losses), must be replaced if the agricultural system is to be sustainable. If this is not done the system is, in effect, 'mining' the soil reserves of plant nutrients, and this will inevitably lead to a decline in soil fertility and productivity. A recent study instituted by FAO revealed a substantial depletion rate of nutrients on arable land in sub-Saharan Africa (38 countries).

Low-input agriculture is sustainable if the balance between export and supplies of plant nutrients is equilibrated. Organic agriculture cannot create plant nutrients except by interception of atmospheric nitrogen through biofixation. Organic agriculture recycles plant nutrients, although with low profitability, as with every biological process, and the area providing these nutrients has to be much larger than the area receiving organic material in order to balance the system. However, in many cases, creating good conditions for insects, worms and micro-organisms in soils, intensive organic agriculture can develop conditions for high soil productivity in well-supplied fields.

Crops require an instant flow of nutrients at special growing stages, which cannot be supplied by natural weathering of mineral and organic material, to ensure higher yields. Organic sources of plant nutrients release these nutrients slowly. This can be a limiting factor, and quickly available fertilizers can provide sufficient plant nutrient flow to the crops. On the contrary, at the early stage of the crops, or with low-demand conditions, organic sources can limit plant nutrient losses by leaching or gas, or avoid fixation of nutrients by soil components, especially in very acidic situations. Thus, plant nutrition management should not be conceived only in terms of balance sheets.

The countries with an urgent need to bring about the quantum jump in agricultural production are also victimized by the vicious cycle of poverty, low-input agriculture and soil degradation. This cycle can only be broken by transforming resource-poor, low-input farming into science-based agriculture. The latter must be based on judicious use of off-farm inputs, because increased and sustained crop production will not be possible without improving and sustaining soil fertility and productivity. The more impoverished an ecosystem, the more inputs are needed to raise economic output.

With low input, the minimum dietary requirement can only be met from about 0.5 ha land *per caput*. The greatest challenge facing mankind in the 21st century is to produce the basic necessities of food, feed, fibre, fuel and raw material from 0.14 ha land *per caput* or less. Technological options for sustainable management of soil, water and plant nutrient resources in the 21st century must address this issue. The *per caput* land requirement to meet the basic needs depends on the inputs.

While the use of mineral fertilizers is the quickest and surest way of boosting crop production, their cost and other constraints frequently deter farmers from using them in recommended quantities and in balanced proportions. The cost escalation resulting from a shift in the policies of many governments, through reduction or withdrawal of subsidies from fertilizers without correspondingly enhancing produce prices, has further aggravated the situation.

These limitations - associated with either source of plant nutrients - are often overcome when they are used in judicious combination providing a mixture which, in the long term, is not only complementary but synergistic. Moreover, environmental hazards attributed to prolonged and sometimes heavy rates of mineral fertilizer application can be reduced by optimizing fertilizer use efficiency through a judicious mixture of organic sources, and mineral fertilizers at levels sufficient to replenish the soil nutrients removed by the crops.

Thus, in recent years, FAO has been actively involved in the development of Integrated Plant Nutrition Systems (IPNS) and their application in developing countries within a holistic nutrient management approach that is ecologically, socially and economically viable, at the same time sustaining soil productivity and ensuring the required levels of crop production.

IPNS CONCEPT

The basic concept underlying IPNS is the maintenance or adjustment of soil fertility and of plant nutrient supply to an optimum level for sustaining the desired crop productivity through optimization of the benefits from all possible sources of plant nutrients in an integrated manner. The appropriate combination of mineral fertilizers, organic manures, crop residues, compost or N-fixing crops varies according to the system of land use and ecological, social and economic conditions.

Farmers all over the world have transformed natural ecosystems into agricultural ecosystems in order to achieve production goals. This transformation happens through the modification of land use, and of farming and cropping systems. It implies modification of the relationships between forests or trees, livestock systems, pastures and cropped areas. This process of transformation cannot be homogeneous because the access of farmers to natural resources, farmers' capital and equipment, and the available labour force on the farm are quite heterogeneous in each region. All these modifications have an impact on plant nutrient management. Therefore, advice for plant nutrient management cannot address stabilized cropping systems and land use but should monitor the modification of plant nutrition management within a general strategy of sustainable increase of land productivity, and has to be organized in options to be selected by farmers according to their conditions and goals.

Indeed, plant nutrient supply to the soil/vegetation system results from the addition of the supply from independent renewable sources (rain, N-fixation, soil weathering and deepening), from the recycling of wastes and by-products generated by the farming systems (dependent and renewable sources), and from the mining of non-renewable sources (soil reserves, mineral fertilizers). During the transformation of a natural ecosystem into an agricultural ecosystem, plant nutrient reserves of the soil/vegetation systems are modified. The level of these reserves is an important factor of sustainability for the use of the land. Soil management within cropping systems is sustainable if the soil conditions are not sufficiently altered to cause the decrease of soil production capacity for given levels of intensification (soil physics, soil plant nutrient storage capacity, plant nutrient supply capacity). However, the mining of plant nutrient reserves decreases the organic matter content, directly through the mineralization of organic matter providing the mined nutrients, and indirectly if the mining process decreases biomass production and the supply of organic material balancing the mineralization of soil organic matter.

The cropping system rather than an individual crop, and the farming system rather than an individual field, are the focus of attention in this approach for developing IPNS practices for the main agro-ecological zones of a country and for the various categories of farms. IPNS identify the best associations of various types of plant nutrients in the different fields for a balanced plant nutrition and higher yield, at the same time sustaining soil fertility and controlling nutrient losses. The Farming System approach helps the farmer in the choice of the most adapted IPNS techniques to any situation and in increasing farm production and labour productivity. It is envisaged that locally-available materials of plant or animal origin as by-products of agricultural activities be used or, where such materials are not abundantly available, *in situ* production of organics be attempted. In areas and farms where non-cultivated areas are available (forests, pastures, fallows), development of biomass production is attempted for a better contribution to plant nutrient transfer to cultivated areas in a sustainable system. In areas and farms where land is scarce and limited to the fields, increasing biomass production in fallows and in the margins of the plots can be attempted. Sources of organic materials which have considerable potential are: quick-growing leguminous crops grown as a part of the cropping system and incorporated into the soil at an appropriate stage as green manure; leguminous trees grown in hedgerows and their loppings used as mulch materials or incorporated into the soil of the cropped alleys between them; forage or food legumes properly inoculated with *Rhizobia* grown in the cropping sequence; and the use of *Azolla* or *blue-green algae* with wetland crops.

The following phenomena must be understood in the context of organic recycling and IPNS: (i) *in situ* recycling of crop residues will bring back a certain amount of nutrients to the same field. However, they are not new sources and are deficient in the same nutrients as those of the soil; (ii) *in situ* growing of leguminous crops/shrubs and their biomass incorporation will bring atmospheric N into the system, and occasionally, through their deep roots, nutrients leached beyond root zone and subsoil mineralized nutrients are brought to the surface layer for the use of annual crops; (iii) when biomass is brought from outside the plot or farm and/or cattle graze on uncultivated land, it is a transfer of nutrients from one place to another. So, except for nitrogen where biofixation can introduce nutrients into the soil-crop system, IPNS is a process which limits the losses in the system and increases the efficiency of nutrients, but not a process which supplies plant nutrients for the whole system. However, such a system can transform biomass with low economic values (straws from savannahs) into biomass with a higher value (maize grain and straw).

Contrary to the 'Low External Input' (LEI) and 'Organic Farming' approaches, the IPNS involve a low to medium external input approach, taking into account a holistic view of soil fertility and plant nutrition management for a targeted yield based not only on cropping and farming systems but also on distinct geographical areas or villages as a dynamic system.

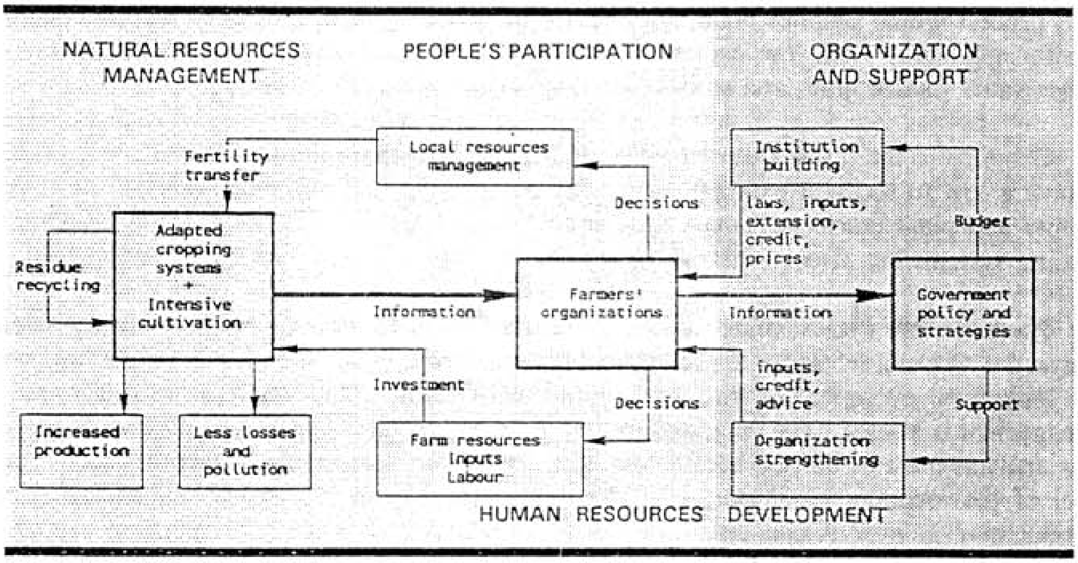
Plant nutrient cycles, plant nutrient transfers and plant nutrient productivity are usefully analysed with clear reference to the original natural ecosystems, when it is possible, and within the long-term evolution of the agricultural ecosystems. The analysis of plant nutrient management is related to an area, and the concepts and methods depend on the size of the area. This analysis must be carried out at field, farm, village or human group territory levels, at the level of the medium-size watershed. The challenge of crop intensification, as far as plant nutrient management is concerned, consists of the increase in the plant nutrient capital, the increase of the productivity of the capital, and the reduction of losses from the cropping system. This challenge must be dealt with at the level of the whole farm, at least, and in many cases at the level of the whole territory of the villages. The IPNS programme of FAO develops innovations and promotes their diffusion for the best use of all sources of plant nutrients in order to upgrade their productivity and to reduce plant nutrient losses. If the fertility of the soil and the plant nutrient content of the soil/crop system have already been lowered to a high degree by inappropriate practices, one major task of IPNS will be at least to stop the unfavourable ongoing evolution, and if possible to upgrade the plant nutrient content of the soil/crop system. This needs better understanding of the constraints and of the efficiency of practices required to rebuild more productive systems than through the simple recycling of organic materials. The role of mineral fertilizers must be clearly defined within the range of practices needed to increase their efficiency and within the complete cycle of plant nutrients involved within the soil/crop system.

FAO PROGRAMMES INSTRUMENTAL IN DEVELOPMENT OF IPNS STRATEGY

The agro-technical concept of IPNS has been enlarged to a holistic development programme (Figure 1) promoting natural resource management through people's participation with the following main components:

- Diagnosis, through people's participation, of social, ecological and economic processes determining current soil productivity.
- Identification of integrated practices of organic recycling, inputs management, soil preparation and cropping patterns.
- Transfer of technology and human resources development.
- Exchange of experience through regional field programme networks.
- Promotion of farmers' organizations to upgrade natural resources management and to purchase inputs.

FIGURE 1
Holistic implementation of IPNS for sustainable agriculture and rural development



- Support for government strategies and policies related to plant nutrition towards sustainable agriculture.
- Collaboration with donor community, international research centres and non-government organizations.

The following is a summary of the global, regional and country-specific activities initiated by FAO:

Global actions

Availability of organic sources and potential of biological nitrogen fixation (BNF)

When planning programmes and activities in organic recycling, it is worthwhile, if not indispensable, to consider all the possible uses of a particular material and to examine if recycling it as a manure is really the best choice. Once this is clear, one can start looking into how the actually available organic materials can be recycled and used as a manure/mulch/soil conditioner in an optimal way. Only then can sound ideas be developed on how to integrate the available nutrient carriers, organic, biological and mineral, in an environment-friendly way which is also socially and economically acceptable to the farmer.

To have a first-hand appreciation of the potential availability of various sources, status reports for selected countries in the Asia and Pacific Region and the Africa Region, covering various aspects of soil fertility and crop nutrition, were prepared. These documents show that the prospects of various organic and biological sources differ from country to country. The following are the main sources, in order of priority:

1.	Bangladesh:	Animal wastes; BNF (*Rhizobium*); green manuring.

2. Indonesia: BNF (*Rhizobium*); recycling of legume crop residues and rice straw; animal wastes.
3. Nepal: Hill areas - animal wastes; BNF (*Rhizobium*). Tarai areas - BNF (*Rhizobium*); green manuring.
4. Pakistan: Animal wastes; BNF (*Rhizobium*); green manuring.
5. Sri Lanka: Recycling of rice straw and legume crop residues; BNF (*Rhizobium*).
6. Thailand: BNF (*Rhizobium*); crop residues; agro-industrial wastes.
7. Burkina Faso: Animal wastes; crop residues; BNF (*Rhizobium*).
8. Guinea Bissau: Crop residues, BNF (*Rhizobium* and *Azolla*).
9. Madagascar: Animal wastes; crop residues, particularly rice straw; BNF (*Rhizobium* and *Azolla*).
10. Rwanda: Animal wastes (in Butare and Gitarama regions); BNF (*Rhizobium*); crop residues.
11. Sudan: Animal wastes; crop residues; BNF (*Rhizobium*).
12. Tanzania: BNF (*Rhizobium*); crop residues.
13. Zaire: Crop residues; forest leaves; BNF (*Rhizobium*).
14. Zambia: Animal wastes (certain areas in southern, western and central provinces); crop residues; BNF (*Rhizobium*).

Although the above assessment was made for planning initial activities, there is a need for a countrywise database on quantification of actual availability and their nutrient contents.

Organization of a database

The organization of a database to collect relevant information for the interpretation of prevalent situations on the farms and the possible impact of proposed IPNS innovations is an important objective. Such a database is being organized at FAO headquarters and also in each project country.

The following are the broad data sets collected from IPNS trials and demonstrations facilitating meaningful agronomic analysis, interpretation and interpolation:

- location of the plots;
- ecological conditions at the level of the landscape unit;
- ecological conditions at the level of the plot;
- agronomic conditions induced by land use and cropping systems;
- cropping system management during the year of the experiment;
- description of the experimental plot;
- measures of crop parameters;
- evaluation of the apparent plant nutrient balance.

The proposed database could eventually be complementary to GIS, Agro-Ecological Zoning and Land Use Planning.

Plant nutrient situation in space and time

Models of plant nutrient cycles in cropping systems and of plant nutrient transfers in a farm or in the territory of a farmers' community will be developed to facilitate assessment of the modification of plant nutrient stocks in soil, residues and wastes according to the exports and losses from and supply to the system and eventually to support the efforts of the extension services issuing adapted messages.

An initial study on Plant Nutrient Balance Sheet Modellization and Assessment of the Analysis of Plant Nutrient Depletion was undertaken in 38 countries of the Sub-Saharan Africa. A meeting of a panel of experts was organized to further discuss the modelling methodology which still needs refinement. To address this, a few country case studies in varying agro-ecological conditions will be undertaken and an expert consultation on modellization will be held.

Concurrent to the nutrient balance modelling, a first-hand attempt was made to develop computer models for an IPNS calculation programme of plant nutrition recommendations based on general agronomic assumptions. This model needs further refinement and validation under varying agro-ecological conditions.

Development of integrated but simple and practical nutrient balance sheet and IPNS recommendation models will be the ultimate objective.

Environmental hazards and pollution from plant nutrient management

Environmental hazards caused by plant nutrient losses, toxic accumulation from plant nutrient supply sources and soil fertility degradation caused by plant nutrient depletion to support the increase of the productivity of the cropping systems are of increasing concern. Risks increase when the use of plant nutrients is increased.

All phosphatic ores and related phosphatic fertilizers contain various amounts of hazardous products. The industrial processes to reduce these products are very costly, and the limited use of ores with low hazardous product contents, limiting the availability of plant nutrients, will increase fertilizer prices, and this will affect mostly poor farmers. The available documentation does not yet substantiate that rather high contents of hazardous products in fertilizers create toxic levels of these products in crops in the long term. Nevertheless, cropping systems and soil management must be designed to limit root absorption of these products. The maintenance of favourable levels of soil CEC and pH, and dilution of hazardous products in crops through high biomass yields, could be a major solution to this problem. Wastes, manures and sludges, through biological concentration processes, can supply to the soil 100 times more hazardous products than fertilizers for the equivalent plant nutrient contents and this is becoming a major environmental problem in peri-urban areas of many developing countries. Organic recycling would not limit this problem.

If the runoff is not adequately controlled and if the rooting system cannot take up plant nutrients in time, intensification increases plant nutrient losses from the crop/soil system (N and K, through runoff and leaching, P through runoff). Through biomass increase, fertilizers contribute to restoring soil organic matter content, but decay of this surplus biomass directly increases plant nutrient losses when rooting systems cannot take up plant nutrients produced in this way (winter, dry season). Although not simple, the integration of cropping patterns, plant population density and rooting system management can solve the problems of plant nutrient losses.

The contribution from agricultural and other biotic sources to greenhouse gas emission is estimated to be 30% in the case of carbon dioxide (CO_2), 70% for methane (CH_4) and 90%

for nitrous oxide (N_2O). New land and crop or animal management techniques need to be devised to reduce these emissions, but avoid losing production potential.

Increasing attention will thus be given to investigation of environmental problems linked with the use of graded levels of organic and mineral sources of plant nutrients, recycling of urban wastes and agro-industrial by-products for plant nutrition in agriculture around towns and in areas close to agro-industries. Principles will be further developed for sound use of mineral fertilizers and organic/biological sources, leading to a Covenant of Good Plant Nutrition Practices.

Documentation

In addition to the existing publications on diverse subjects, it is proposed to bring out a consolidated publication "Plant Nutrient Management in Cropping Systems". A meeting of a panel of experts was organized to decide on the contents and contributors. It is expected that the publication would be ready towards the end of 1995.

Regional/country-level activities

Field Trial Network

To generate specific information on combined applications of organic/biological sources with mineral fertilizers in different agro-ecological situations and dominant cropping systems, long-term trials are being undertaken in India, Indonesia, Laos, Nepal, Pakistan and Thailand under research agreements with leading institutions in these countries. These trials are expected to generate basic information related to specific organic and inorganic plant nutrients interventions and would allow extrapolation to test them in adaptive trial sites within IPNS field projects.

As an illustration, results from one site each in India and Pakistan with wheat-rice (irrigated) cropping systems are given below:

India

An experiment was conducted for 6 years in the Punjab Agricultural Research Institute farm, Ludhiana. The soil was sandy loam with pH 7.3 and containing 0.29% organic carbon, 112 N kg/ha, 18 P kg/ha and 110 K kg/ha. The wheat was grown under two fertility levels: low 60-30-30 and high 120-60-60 kg/ha N, P_2O_5 and K_2O, respectively. After wheat, each main plot was subdivided into 3 sub-plots: (i) growing of summer mung (*Vigna radiata*) with 12.5 N and 40 P_2O_5 kg/ha, first picking of grain harvested (about 1 t/ha) and halmes incorporated (average of 2.5 t/ha dry matter containing 60 N kg/ha); (ii) growing of sesbania (*Sesbania aculata*) and incorporation at 45 days (average 4.5 t/ha dry matter with 110 N kg/ha); (iii) FYM at 10 t/ha (4 t/ha on dry weight basis with average content of 68 N, 36 P_2O_5 and 74 K_2O kg/ha) applied. Each sub-plot was further subdivided into four receiving 60-0-0, 60-30-0, 60-30-30 and 90-30-30 N, P_2O_5 and K_2O, respectively. In addition, a fallow plot was maintained as a control which received 120-30-30 N, P_2O_5 and K_2O kg/ha, respectively. Rice was then transplanted.

Although the limitations of the experimental design for a full interpretation is recognized, from the results given in Table 1 the following broad conclusions can be drawn:

TABLE 1

Effect of manures and fertilizers on the yield of rice and wheat grown on a rotation at two fertility levels in Ludhiana, India

Treatments ($N-P_2O_5-K_2O$ kg/ha)	Rice yield (t/ha)							Wheat yield (t/ha)							Total (Rice + Wheat) (t/ha)	Soil analysis after 12 crops		
	1985	1986	1987	1988	1989	1990	Total	85-86	86-87	87-88	88-89	89-90	90-91	Total		OC%	P (kg/ha)	K (kg/ha)
Low fertility (60-30-30 wheat)																		
SM + 60-0-0	7.3	6.1	5.9	5.6	5.7	2.3	32.9	3.4	3.4	4.3	4.3	4.1	4.2	23.7	56.6	0.46	21	96
SM + 60-30-0	7.3	6.1	6.0	5.7	5.9	2.2	33.2	3.0	3.5	4.2	4.4	4.1	4.2	23.4	56.6	0.45	23	102
SM + 60-30-30	6.9	5.8	6.0	5.7	5.8	2.7	32.9	3.3	3.4	4.2	4.2	3.9	3.9	22.9	55.8	0.44	24	104
SM + 90-30-30	7.4	6.4	6.3	5.9	6.0	2.3	34.3	3.6	3.2	4.2	4.3	3.9	4.0	23.2	57.5	0.47	21	98
SB + 60-0-0	7.2	6.2	6.1	5.8	5.3	2.5	33.1	3.5	3.4	4.1	4.3	4.1	4.1	23.5	56.6	0.48	19	106
SB + 60-30-0	7.2	6.5	5.9	5.8	5.4	2.6	33.4	3.5	3.5	4.2	4.3	4.0	4.1	23.6	57.0	0.50	22	106
SB + 60-30-30	7.2	6.6	6.4	6.0	5.2	2.3	33.7	3.3	3.4	4.3	4.5	4.0	4.1	23.6	57.3	0.52	23	107
SB + 90-30-30	7.4	6.5	6.7	6.2	5.5	2.9	35.2	3.5	3.2	4.3	4.5	4.3	4.1	23.9	59.1	0.46	20	104
FYM + 60-0-0	6.2	5.3	5.5	5.4	5.0	2.3	29.7	3.3	3.3	4.3	4.6	4.3	4.4	24.2	53.9	0.53	27	102
FYM + 60-30-0	5.7	5.6	5.4	5.0	4.8	2.5	29.0	3.8	3.4	4.1	4.6	4.5	4.1	24.5	53.5	0.48	27	99
FYM + 60-30-30	5.8	5.7	5.4	5.5	4.9	2.4	29.7	3.4	3.2	4.1	4.5	4.3	4.4	23.9	53.6	0.56	24	103
FYM + 90-30-30	6.5	5.7	6.1	5.8	5.2	2.3	31.6	3.2	3.1	4.2	4.5	4.1	4.2	23.3	54.9	0.49	25	105
120-30-30	6.3	5.8	5.9	5.3	5.0	2.1	30.4	3.5	3.3	4.2	4.1	3.9	3.7	22.7	53.1	0.42	16	87
High fertility (120-60-60 wheat)																		
SM + 60-0-0	7.3	6.5	6.1	5.8	6.0	2.5	34.2	4.8	4.4	4.3	5.8	4.8	5.2	29.3	63.5	0.48	24	104
SM + 60-30-0	7.1	7.1	5.9	5.5	5.8	2.9	34.3	4.5	4.7	4.7	5.7	4.9	5.2	29.7	64.0	0.49	20	115
SM + 60-30-30	7.3	7.4	6.0	5.7	5.7	2.6	34.7	4.8	4.4	4.7	5.6	4.9	5.1	29.5	64.2	0.46	28	108
SM + 90-30-30	7.6	7.0	6.4	5.8	5.6	2.9	35.3	5.0	4.2	4.6	5.8	5.2	4.8	29.6	64.9	0.52	23	111
SB + 60-0-0	7.3	6.5	6.2	6.0	5.6	2.1	33.7	4.2	4.5	4.4	5.6	5.3	5.1	29.1	62.8	0.47	23	101
SB + 60-30-0	7.3	6.6	6.1	6.0	5.7	2.6	34.2	4.7	4.8	4.6	5.5	5.0	5.2	29.8	64.0	0.44	23	103
SB + 60-30-30	7.3	6.7	6.0	6.2	5.7	2.5	34.4	4.4	4.5	4.4	5.6	5.2	4.8	28.9	63.3	0.48	24	110
SB + 90-30-30	7.7	6.6	6.4	6.4	5.6	2.7	35.4	4.7	4.3	4.5	5.5	5.2	5.1	29.3	64.7	0.52	26	105
FYM + 60-0-0	6.1	6.6	5.8	5.1	4.8	2.2	30.6	4.9	4.4	4.7	6.1	5.4	5.4	30.9	61.5	0.49	31	105
FYM + 60-30-0	5.9	6.0	5.7	5.3	4.9	2.6	30.4	4.7	4.5	4.7	5.1	5.2	5.2	30.4	60.8	0.55	33	99
FYM + 60-30-30	6.3	6.2	5.8	5.3	4.5	2.4	30.5	4.7	4.4	4.7	6.3	5.1	5.1	30.3	60.8	0.53	27	103
FYM + 90-30-30	6.5	6.2	6.0	5.7	5.3	2.1	31.8	4.5	4.2	4.6	6.1	5.3	4.9	29.6	61.4	0.51	31	109
120-30-30	6.5	6.4	6.0	5.6	5.4	2.3	32.2	4.6	4.5	4.7	5.6	5.0	4.6	29.0	61.2	0.42	21	97

- ☐ Yield of wheat under the high fertility level is higher than under a low fertility level, however with very limited residual effect on rice.
- ☐ Green manuring with summer mung or sesbania with an application of 60 N kg/ha increased the yield of rice over that obtained with only 120-30-30. Application of FYM at present level did not show any yield improvement in rice; however, it showed a better residual effect on wheat, unlike green manuring.
- ☐ No response to phosphate and potash applications was observed.
- ☐ From the total yield of 6 crops each of rice and wheat, it is clear that application of FYM with 60 N kg/ha in rice with constant fertilizer application in wheat produced similar yields as obtained by the application of 120-30-30 in rice. Green manuring with 60 N kg/ha outperformed any other treatments. Additional grain obtained from summer mung is a bonus and could more than compensate additional N and P_2O_5 given to this crop.
- ☐ From the soil analysis data it is observed that organic carbon content increased under all treatments; the maximum with FYM, followed by green manuring and only fertilizers. Available phosphorus also followed a similar trend, with minor depletion under rice 120-30-30 and wheat low fertility treatment. A slight depletion of potassium was recorded under all treatments, the extent being higher under rice 120-30-30 and wheat low fertility treatment. Organic manures improved soil physical conditions (such as infiltration rate and bulk density). Sesbania green manuring showed best results.
- ☐ With an over-simplified conclusion it can be stated that green manuring prior to rice and application of 60 N kg/ha to rice and 120 N, 60 P_2O_5 and 60 K_2O kg/ha in wheat would be optimum for a production of 10.5 t/ha of grain. If green manuring would not be possible, then replacement of green manuring could be done by addition of 4 t/ha of FYM (dry weight basis).

Pakistan

An experiment was conducted for 2 years in the farm of the Ayub Agricultural Research Institute, Faisalabad. FYM, guar (*Cyamopsis tetragonoloba*), sesbania and wheat straw with one fallow treatment were applied in main plots before rice and four rates of fertilizers (N, P_2O_5, K_2O 40-30-0, 80-60-0, 120-90-0, 120-90-60) were applied both for rice and wheat. Guar and sesbania were incorporated after 42 days from sowing. The soil was a sandy loam with pH 7.6.

Although the experiment is being continued, from the results of 2 years (Table 2), the following broad conclusions can be drawn:

- ☐ Aggregated over the four crops, FYM gave best yields compared with other organic sources without any fertilizers or absolute control (no organic addition).
- ☐ Wheat straw had no beneficial effect on yield. A farmer in these conditions would be wise to remove crop residues and use them for other purposes.
- ☐ Effect of potash on yield appears negligible. Increasing levels of N and P had a positive effect.

TABLE 2

Effect of manures and fertilizers on the yield of rice and wheat grown on a rotation in Faisalabad, Pakistan

Treatments (N-P_2O_5-K_2O kg/ha)		Grain yield (t/ha)					Straw yield (t/ha)
		Paddy 1991	Wheat 1991-92	Paddy 1992	Wheat 1992-93	Total	Total
FYM	+0-0-0	3.29	1.67	3.20	1.41	9.57	16.99
	+40-30-0	3.69	2.87	3.18	2.54	12.28	22.04
	+80-60-0	3.73	4.20	2.74	3.52	14.19	26.17
	+120-90-0	4.15	4.70	3.36	4.23	16.44	31.20
	+120-90-60	4.03	4.60	3.65	4.69	16.97	30.34
Guar	+0-0-0	3.33	1.67	2.49	0.99	8.48	14.35
	+40-30-0	4.26	3.28	3.43	2.65	13.62	23.51
	+80-60-0	4.20	3.87	3.18	3.25	14.50	25.17
	+120-90-0	4.85	4.63	3.43	3.48	16.39	30.19
	+120-90-60	4.45	4.20	3.80	4.08	16.53	31.26
Sesbania	+0-0-0	2.21	1.87	2.83	1.51	8.42	16.31
	+40-30-0	3.98	3.20	3.55	3.07	13.80	22.94
	+80-60-0	3.98	3.87	3.43	3.63	14.91	27.24
	+120-90-0	4.81	4.13	3.61	3.95	16.50	26.90
	+120-90-60	4.23	4.80	3.43	4.52	16.98	28.98
Wheat straw	+0-0-0	2.85	1.72	2.18	1.28	8.03	12.68
	+40-30-0	3.28	3.20	2.87	2.41	11.76	18.62
	+80-60-0	3.95	4.18	3.24	3.71	15.08	25.18
	+120-90-0	4.30	4.04	3.02	3.94	15.30	28.28
	+120-90-60	4.23	4.28	3.17	3.94	15.62	27.08
Fallow	+0-0-0	2.65	1.68	2.93	1.35	8.61	14.23
	+40-30-0	3.25	3.00	3.08	2.16	11.49	19.64
	+80-60-0	3.97	3.95	3.36	3.35	14.63	25.29
	+120-90-0	4.07	4.67	3.11	4.13	15.98	28.10
	+120-90-60	4.13	4.67	3.61	3.89	16.30	29.79

- Organic sources addition (FYM and green manuring) did not reflect a significant effect on yield, except when applied with lower rates of NP (40-30); both grain and straw yield were better than with a NP (40-30) only application.

- From the rice yield increase, guar could be rated best organic source. However, when both crop yields are considered, sesbania looks more promising. On the other hand, yield of straw under FYM and guar appeared to be higher compared to other treatments.

- From the soil analysis results (Table 3), it can be seen that addition of FYM and sesbania green manuring improved total N and available P and K content of soil considerably when compared with other organic sources and control. Although there has been varying magnitude of build up of all nutrients under all treatments, most strikingly levels under guar are lower than even under control. The positive effect of NPK contribution through FYM and sesbania has not yet been fully reflected on crop yields.

TABLE 3
Effect of manures and fertilizers applied in a rice-wheat rotation on the soil N, P and K levels in Faisalabad, Pakistan

Treatments	Total N (%)			Available P (ppm)			Available K (ppm)		
	Before expt.	After 3 crops	Increase	Before expt.	After 3 crops	Increase	Before expt.	After 3 crops	Increase
Fallow 0-0-0	0.050	0.064	0.014	5.67	8.84	3.17	154	170	16
FYM (16.6 t/ha) containing N 198-P_2O_5 168-K_2O 601	0.041	0.067	0.026	5.99	12.45	6.46	138	202	64
Guar (1.1 t/ha) containing N 36-P_2O_5 7-K_2O 48	0.050	0.060	0.010	6.55	7.83	1.28	156	155	-1
Sesbania (3.9 t/ha) containing N 160-P_2O_5 35-K_2O 178	0.038	0.060	0.022	3.20	8.58	5.38	126	157	31
Wheat straw (4.4 t/ha) containing N 17-P_2O_5 3-K_2O 71	0.050	0.063	0.013	6.53	9.24	2.71	150	157	7

Except in India, Pakistan and Thailand, network trials have not been conducted satisfactorily in Nepal, Laos and Indonesia. In the meantime, a number of country projects with a strong IPNS component have been formulated and thus future trial activities will be integrated within these project activities.

Asian Network on Bio and Organic Fertilizers

The Asian Network on Bio and Organic Fertilizers was formed in 1988 and has subsequently been joined by 19 government and parastatal focal institutions concerned with bio and organic fertilizer research and development from 13 Asian countries. The Secretariat of the Network is provided by FAO's Regional Office for Asia and the Pacific in Bangkok, Thailand.

The overall objectives of the Network are to contribute to improving and maintaining soil fertility through the rational and complementary use of biological and organic plant nutrient resources and mineral fertilizers. In pursuance of these objectives the network undertakes the compilation and dissemination of country-wise information and documentation on methodologies and innovative techniques in regard to the introduction of bio and organic fertilizers in integrated plant nutrition systems. The network maintains a directory of resource persons cross-referenced by country and field(s) of interest as well as a computerized reference database.

The network meets biennially and the proceedings are published by FAO's Regional Office. Topics covered by network meetings to date are: "Bio and Organic Fertilizers: Prospects and Progress in Asia", "Asian Experiences in Integrated Plant Nutrition" and "The Role of IPNS in Sustainable and Environmentally-sound Agricultural Development". In addition, network news is featured in the annual bulletin, "Organic Recycling in Asia and the Pacific", published by FAO's Regional Office for Asia and the Pacific.

Development of IPNS technologies and their transfer

The results of the IPNS Network allow identification of alternatives and formulation of nutrient recommendations for a cropping system at **plot level**. However, in reality, the IPNS approach needs to be implemented at **farm level** and even at **village level**. At farm level, possible alternatives identified at plot level are to be integrated according to the production goals of the farmer and to general availability of resources, to ensure the highest benefits and higher labour efficiency. In many areas, the IPNS approach cannot be implemented at farm level because the resources used to sustain the system are available at village level, i.e. transfer of litter from surrounding forests, relationships between pastures and cultivated areas through manure use, collective use of residues by cattle after harvest, etc. Thus, the IPNS Network is being integrated with the IPNS-type Field Projects Network to develop location-specific models and their adoption through farmers' participation. Field projects in Ethiopia, Tanzania, Rwanda, Niger and Nicaragua already have some IPNS elements. The ongoing Bolivia project and pipeline projects in Nepal, Bhutan and the Himalayan region are fully tailored to the IPNS approach. All future projects will be developed with the same approach.

The atmospheric fixation of nitrogen by micro-organisms constitutes the most important entry of nitrogen in the nitrogen cycle and, thus, is an important component of the IPNS approach. The following are some illustrations of specific field activities in this field:

- In Rwanda, a study has been undertaken on the influence of inoculation on nodulation and yield of common bean compared to climbing bean. The influence of nitrogen fixation on the elaboration of yield components is studied in common bean and climbing bean.

- In Burundi, an indigenous strain of Rhizobium-producing nodules with bush bean has been isolated and gives better yield increases in greenhouse trials and in the first experiments in the field than the reference strain. It will be necessary to introduce it in different agro-ecosystems of the regions and in symbiosis with various varieties.

- A new project, funded by UNDP, to improve the production of inoculants for legumes in Zaire, has been initiated.

- In India, the National Biofertilizer Development Centre is dealing with rhizobial inoculant production and quality control. Members of the NBDC and Regional Biofertilizer Development Centres have been trained in MIRCEN, Bangkok. A strain collection is maintained in order to serve as reference for private inoculant producers.

- A TCP project is implemented in Syria, assisting the Government in producing good quality inoculants for legumes, mainly for soybean. A production laboratory will be installed and researchers trained in microbiological technology used for preparing good quality inoculants.

Since AGLN no longer has any BNF expert, more collaboration will be established with other Divisions, especially the joint FAO/IAEA Division.

The development of IPNS cannot be promoted without an extensive participation of farmers selected for their social representativeness in every ecological condition. The development of IPNS includes a major modification of traditional extension practices, as IPNS cannot be developed with blanket recommendations. The extension services should rely on a panel of alternative proposals, for which all necessary conditions of efficiency are identified in reference farms, representative of socio-economic and ecological conditions in the region.

Within FAO's IPNS field projects, an intensive diagnosis of plant nutrient management in cropping system and natural resource use is implemented first at village level to design biomass transfers, resource appropriation rules between farmers and land use pattern. This analysis is used in selected villages on the basis of Agro-Ecological Zonation and of Socio-Economic Zonation of the area. Cooperation with research teams on farming systems is established to identify the various farm categories in relation to their access to natural resources, their labour availability and production requirements, equipment level, specialization for cropping systems and animal husbandry, production objectives, and cash flow availability.

Within selected farms from these categories, a thorough analysis is implemented to make balance sheets (apparent) of plant nutrients, balance sheets of organic material production, transfer and use in each plot and in the whole farm. External supplies of plant nutrients and organic matter from collective lands are estimated. Cropping patterns are analysed with productivity evaluation and allocation of plant nutrients and organic matter is compared to plot productivity. Implementation of agricultural practices throughout the cropping seasons is discussed with each farmer to understand the rationale of crop rotation, cropping pattern, labour and input allocation. Comparison of agricultural practices, organic material management and input use with related yields between the selected farms allows the identification of social and economic determinants of farmers' technical behaviour. This review is the basic process in local conditions to be introduced directly into selected farms. Also, a network of peripheral trials, in strictly controlled conditions, is implemented to compare advantages and constraints of these innovations for the cropping systems under the conditions of the farm. Promising innovations are introduced in the selected farms (reference farm).

When farmers are sufficiently aware of the interest of the IPNS approach, they are advised to try to modify their farm management, integrating innovations in the whole farm and not only in a plot trial. A contract is discussed with the farmers, in which all technical and financial terms of common action are examined. FAO safeguards against the risk of the experience on the basis of control plots in the traditionally-managed farms. The selected farm then becomes a pilot farm. FAO has a special interest in analysing the development track followed by pilot farms under the innovations proposed and accepted by the farmers because it reveals the possibilities for modification of the current situation through the already tested innovations.

Working through pilot farm networks reveals disconnection of interest and behaviour of farmers from various social origins in the same region and modifications proposed by farmers who faced the same type of economic problems with varying access to natural resources. The implementation of these networks over a minimum of four years allows the interpretation of risk impact on innovations and of risk management by farmers.

Innovations confirmed and evaluated in pilot farms are proposed to other selected farmers so that they can demonstrate the usefulness and economic interest of these innovations in their villages.

Local results have an immediate interest for farmers involved in the project. Nevertheless, local results inserted in large collections of information can be used more extensively if appropriate interpretation allows extrapolations to other situations. Therefore, FAO is attempting to collect available documentation on the IPNS approach and farming system management for plant nutrition from its ongoing projects and from sources external to FAO to organize this documentation for adapted application to the fields. This needs well-established collaboration with national and international institutions, and with active NGOs on the matter to ensure common action on people's participation in designing plant nutrient management within the IPNS approach.

It is also foreseen to form a task force of experts to advise on policy and strategy for the programme, to assist in review missions on the field projects and to contribute to publications.

National strategy

To provide a framework for national strategies for the conservation and regeneration of soil productivity, the following activities are being initiated within the framework of the IPNS-type of field projects:

- Identification and appraisal of all currently and potentially available sources of plant nutrients - organic and mineral - at country level. Review technical and economic potentials (of potential supply sources, including any national deposits, energy sources, improved organic supplies, recycling, wastes, BNF). Assessment of options for use of these additional/alternative sources of nutrient supplies.

- Formulation of alternative strategies to meet future demand for soil fertility development and maintenance, including policy options with regard to prices, incentives, subsidies and taxes, including: (a) integration of organic and mineral sources of plant nutrients in a system to sustain soil fertility (IPNS); (b) quantification of mineral fertilizer needs, either produced locally or imported.
- Preparation of national action plans for the sustainable development and maintenance of soil productivity, incorporating the mobilization of advisory services, technical assistance, aid-in-kind, revolving funds, and demonstration programmes for the implementation of best management practices.

A series of national programmes and projects may then follow, expanding upon experience gained through the activities of the FAO Plant Nutrient Management Programme.

CONCLUSIONS

The realities, urgencies and pressures on the land indicate that cropping intensity will increase and the opportunity of fallow for recuperation of soil fertility will be reduced in most developing countries. Nutrient removal will thus increase, resulting in greater soil depletion. The challenge is to halt this depletion and sustain crop production and soil productivity.

All possible sources of plant nutrients (organic, bio and mineral) are important and need to be exploited. Each source has its own merit and limitation. Thus, a rational and integrated approach will be appropriate to any situation.

IPNS are evolutive, as from the present situation the plant nutrient gains from better management are reinvested in the plant nutrient cycles in order to increase gradually the plant nutrient capital available on the farm: soil reserves, crop residues and manures, and cash flow for the purchase of mineral fertilizers, to restore the natural resource base through the upgrading of the management of village territory and to increase the production of the farmers' labour. For example many soils in sub-Saharan Africa are so deficient in nutrients that there are essentially no nutrients to be cycled. Crop yields are low, and little organic residue is left to protect soils from degrading erosion. Even legumes produce poorly on these soils. Nutrients from outside the biological system must be added to restore the situation. In some parts of Asia farmers have reached the optimum level of nutrient application, particularly N, and the efficiency is decreasing sharply. Under such situations organic sources along with the supply of other imbalanced nutrients will not only substitute N but also increase its efficiency and productivity of the soil.

Thus, a diversified approach to plant nutrition management through IPNS strictly determined according to ecological, economical and social conditions and through the full participation of farmers themselves is taken. The activities fostering the IPNS approach can be classified as:

- Testing of various organic sources and their complementarity towards arriving at an integrated recommendation on a representative experimental site for a cropping system through the IPNS Field Trial Network.

Although some basic information has been generated and can be further generated, it is felt to be quite expensive and difficult to manage and coordinate. Thus FAO could gainfully act as a catalyst in promoting well-planned long-term trials implemented by national research systems with strong collaboration from the international research organizations. A collaborative approach should be promoted.

- Diagnosis of plant nutrition management practices and inventory of plant nutrient sources (their content and how they are managed) based on agro-ecological conditions.

  Although efforts are underway through AGLN's field projects and Broad Context Appraisals in some limited countries, much more still needs to be done to organize a global information database at FAO. Coordination with GIS, agro-ecological zoning and land use planning needs to be strengthened.

- Testing of plant nutrient management innovations from territory/village to the farm to the plot and their transfer through farmers' groups.

  This core IPNS work is attempted through the field projects. This exercise will take a couple of years to arrive at some tangible results. Based on representativeness, probably some modelling could be attempted on a sub-regional basis and tested. In all fairness, it is expected that some blueprints for integrated nutrient supply/management will be developed for advisory services. In view of the limited number of country projects which do not represent all diverse ecologies, a global project with regional networks could certainly be worth considering.

While the above exercise is a long-term agenda, some simplified steps to be taken on an urgent basis to address (how imperfect they may be) two major issues: the growing nutrient depletion and low plant nutrients use efficiency. AGLN, through its field projects, is definitely in an advantageous position to address them. Following are a few proposals:

- Various estimates of fertilizer equivalent of major organic manures and biofertilizers are available. Where appropriate, maximum use of these materials should be made. Because nutrient application rates in most areas are well below optimum, addition of these resources can help to raise the nutrient addition towards optimum.
- Promote improved methods of conservation (enhancing quality) and use of FYM.
- Promote improved methods of compost making and its application.
- Promote inclusion of legumes in cropping systems and their inoculation with suitable strains where feasible.
- Promote balanced fertilization and pay much more attention to management practices to improve the fertilizer use efficiency.
- Assess agronomic efficiency of local mineral resources and promote their use.
- Assess agronomic efficiency of agro-industrial by-products, and household and town refuse, and promote their use.

From the fertilization of crops to the management of plant nutrients in crop rotations and farming systems: an overview

Crops require mineral nutrients and for successful cropping the supply must be adequate. Since the natural nutrient resources, especially those from the soil, can only provide part of the crop requirements, additional nutrients from different sources must be used. The concept of fertilization in its modern comprehensive form, based on improved soil fertility, has proved to be a powerful tool for enormous yield increases.

Due to a high nutrient input, however, the 'capital' of farm nutrient resources has been somewhat neglected. Furthermore, a sometimes careless nutrient use did result in negative side-effects on environment. It is therefore necessary to put more emphasis, beyond the crop nutrient requirements, on the farm internal and external nutrient cycles. The goal must be a better utilization of the nutrients cycling on the farm, to prevent avoidable losses and to minimize expensive inputs. For the different farming systems there are special goals of nutrient management ranging from soil exploitation to sustainable farming with low or high inputs.

In areas with an increasing population, and with most of the people living in towns, consumers place considerable demands and economic pressure on agriculture to the extent of being partly responsible for undesirable production methods.

In order to achieve a sustainable, high and profitable agricultural production, the concept of modern fertilization and the principle of sustainability should be combined into an 'integrated plant nutrition system'.

CROP PRODUCTION, PLANT NUTRIENTS AND SOIL FERTILITY

Farmers want to obtain high yields of food crops and other products from their fields for consumption and sale. Therefore they should provide optimum conditions for crop growth adapted to the particular climate:

- efficient crop variety and agronomic cultivation methods;

PAPER 1.3

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- good soil conditions (structure etc.) through tillage and amendments;
- adequate supply of plant nutrients;
- good protection against crop diseases and pests;
- weed control.

Most of the food sold from farms is consumed in towns or large cities. The consumers want sufficient, good and cheap food. These demands are largely fulfilled in countries with efficient and stable production conditions but place considerable strain on agriculture and influence production methods.

Plant nutrients

For optimum use of nutrients it is essential to know the crops' needs: the kinds and amounts required, as well as their optimum combination with other growth factors. Although plants contain practically all natural elements, the requirements of agricultural plants (crops) are mainly for 13 essential *mineral nutrient elements* and for some *beneficial* ones (Synopsis 1). They are commonly abbreviated to 'nutrients'. This term is also synonymously used for the large number of nutritive substances (ions, molecules) taken up by plants.

Synopsis 1: Essential and beneficial mineral nutrients for plants

\# **13 essential mineral nutrients** required for growth of green plants
- *6 macronutrients* (critical contents 2 - 30 g/kg of dry matter)
  - 3 primary nutrients: N = Nitrogen, P = Phosphorus, K = Potassium
  - 3 secondary nutrients: S = Sulphur, Ca = Calcium, Mg = Magnesium
- *7 micronutrients* or *trace elements* (critical contents 0.3 - 100 mg/kg)
  - 5 heavy metals: Fe = Iron, Mn = Manganese, Zn = Zinc, Cu = Copper, Mo = Molybdenum
  - 2 non-metals: Cl = Chlorine, B = Boron

\# **Some beneficial nutrients** (useful for some plants):
- Na = Sodium, Si = Silicium, Co = Cobalt
- Cl = Chlorine (beneficial beyond being essential), Al = Aluminium (?).

For humans and farm animals some additional elements are essential and should be taken into account, namely Co, Se, Cr, Ni, Sn, V, As, I, F.

In addition to the nutrients, beneficial organic substances taken up by crops from the soils should be considered: growth substances, antibiotics, etc. In view of some by-products of mineral fertilizers (e.g. Cd), of polluting substances from air, water or of industrial and communal waste products, some dangerous or potentially toxic substances must also be taken into account, especially some heavy metals or even some toxic organic substances.

The plant nutrients regulate crop growth together with climatic factors and water supply. The response of crop growth and yield formation to the nutrient supply can be expressed in growth or yield curves and described by 'yield laws'. In practical cropping, nutritive minimum factors are often responsible for unsatisfactory yields and soil fertility problems. Therefore a proper nutrient management is of fundamental importance for effective, successful and sustainable agriculture.

Soil fertility (productivity)

The best use of nutrients for crop growth can be obtained on the basis of a high soil fertility level. Soil fertility is a complex term including many components: soil depth, texture and structure (pore space for supply of oxygen and water), soil reaction, humus content and composition, activity of soil organisms, nutrient content, storage capacity for nutrients, content or absence of detrimental or toxic substances. The result of an adequate combination of these factors is an optimum soil fertility with a high crop production potential (Synopsis 2).

Synopsis 2: Optimum soil fertility

A productive soil with (natural or man-made) high fertility:

- permits a deep penetration for crop roots
- stores and supplies sufficient water
- maintains good soil aeration for the oxygen demand of roots
- mobilizes soil nutrients from the reserves (according to crop requirements)
- stores (soil-borne and fertilizer-derived) nutrients in forms easily available to roots, but protected against losses
- transforms non-water soluble fertilizer nutrients into easily available forms
- buffers nutrient surpluses by (inorganic or organic) immobilization (without fixing them into unavailable forms)
- enhances a high utilization rate of fertilizers (nutrient sources)
- offers a balanced nutrient supply due to its self-regulating system
- fixes unwanted toxic substances (e.g. from emissions or waste products).

Very fertile and thus productive soils are rarely found in nature. Unfortunately, most soils are far from being ideally fertile and should therefore be improved, not only by adding nutrients, but also by special inorganic and organic soil amendments, e.g. lime for correcting strong soil acidity, organic matter for maintaining the activity of 'soil life', structure stability, etc. A good soil fertility, which is mostly man-made, should be maintained and stabilized to endure infinitely, or at least for many centuries.

CONCEPTS OF (MINERAL) FERTILIZATION

The requirements and realization of an adequate nutrient supply are the subject of fertilization. Since most soils do not have sufficient nutrients for the demands of high-yielding crops, even with the additional nutrients from farm waste products, additional nutrients have to be added, i.e., mineral fertilizer is required.

Since its beginning, about 1880, mineral fertilization of crops developed in several steps:

- *Partial fertilization* with primary nutrients (N, P, K) in order to eliminate strong deficiencies which were serious growth minimum factors; furthermore amelioration of soils, e.g. with lime.

  Success: Remarkable yield increases from low to medium yields were obtained, furthermore often a better food and fodder quality. Limits: Even high fertilizer rates were rather frequently inefficient because other (unknown) nutrients became minimum factors; food and fodder quality was sometimes inadequate due to unbalanced nutrition of crops.

- ▫ *Complete fertilization*, i.e. consideration of all nutrients (especially secondary and micronutrients which are not sufficiently supplied by the soil); the goal is to make full use of the photosynthetic capacity of high-yielding crops by means of:

  - optimum (complete) nutrient supply during all growth stages as the basis for high yields, high food or fodder quality and also a certain resistance of plants against stress factors (climatic, pathogenic, etc.)

  - improvement of poor soil fertility or maintenance of a high one (as an indispensable basis of growth promotion).

  Success: Enormous yield increases from medium to high levels as well as generally good food and fodder quality. Limits: The high potential yield could not always be obtained because of other yield limiting factors outside the area of nutrition; furthermore water pollution and disease resistance problems due partly to excessive use of nitrogen.

- ▫ *Comprehensive (integrated) fertilization* as a complete fertilization within the framework of optimum agronomic methods (such as optimum water supply, tillage and crop protection (integrated cropping) in order to make more efficient use of fertilizers and have less avoidable losses.

  Success: Still further yield increases up to a very high level. Limits: High management skills required; some factors (like weather) still remain uncontrollable; the soil nutrient status still remains difficult to estimate (diagnosis of nutrient supply can only be approximative; economic stress can prevent anti-pollution measures).

Shortcomings of practical fertilization (vs. modern fertilization concept):

- ▫ Very high or even too strong reliance on mineral fertilizers, especially nitrogen (most fertilizer research work is centred on N); this 'powerful tool' is often used in excess with the expectation of very high yields beyond realistic yield potentials.

- ▫ The diagnostic methods for the nutrient status (even though only approximate) are not sufficiently applied; fertilization still relies heavily on 'rule of thumb'.

- ▫ Avoidable nutrient losses are often high because there is a tendency to waste fertilizers, especially if they are cheap compared with product prices (losses tend to be neglected when fertilization is 'economic').

- ▫ Unbalanced fertilization with negative effects on quality and crop resistance.

SHIFTING FROM FERTILIZATION TO PLANT NUTRIENT MANAGEMENT

The fertilization concept, especially with high input, has proved to be very effective and has resulted in enormous production increases. In practice, however, they were often combined with several negative side-effects, especially on environment. For these and other reasons a more efficient use of nutrients is required. Furthermore, there will be increasing public demand for restrictions of fertilizer use (e.g. in drinking water resource areas) and of the use of industrial and communal waste products in agriculture.

The necessity of adopting a wider concept of nutrient use (vs. crop fertilization) thus results from shifts in several aspects:

- from individual crop nutrient requirements to optimum use of nutrient sources;
- from static nutrient balances to nutrient flows (fluxes) and nutrient cycles;
- more attention to the unwanted side effects of fertilization (soils, weed growth, crop diseases etc.; pollution of water and air);
- from first year's nutrient effects to long-term effects (residual nutritive effects, fate of non-used nutrients, storage, carry-over);
- beyond yield effects to resistance of crops against stress conditions (dry, cold, salty, alkaline, toxicity, pollution, 'spraying');
- from the assumption of ideal growth conditions to an awareness of not or hardly controllable growth limiting factors and production risks;
- from exploitation of soil fertility to its improvement or maintenance;
- from the neglect of protective restrictions against dangerous or even toxic elements.

PLANT NUTRIENT SOURCES AND THEIR EFFECTIVE USE

Plant nutrients are components of inorganic and organic compounds, or of complex products, which are the *nutrient sources*. In a wide sense, most of them could be termed fertilizers (organic and mineral). Since the list of such sources would be very long, they are presented here in a summarized version (Synopsis 3). Many of these sources, however, contain also unwanted substances, e.g. toxic heavy metals.

Many nutrient sources are freely available on the farm, some can be obtained by extra activity of the farmer, some must be bought. Several sources can be used alternatively (potential compensation).

Soil nutrients

The soil nutrients are the basic source of the farm nutrient supply. Part of them can be utilized by crops, i.e. the easily available portion (water-soluble, exchangeable) as well as the easily mobilizable, accessible fraction. The mobilization of nutrients from mineral and organic non-available sources can to a certain extent be enhanced by activating soil life (by organic matter or special *biofertilizers*), by strongly mobilizing plants, better accessibility (structure improvement), soil burning, deepening of the plough layer or fallow periods. Subsoil or parent material can be transferred into the topsoil (root zone) in order to supply new weatherable minerals, lime, etc.

The non-compensated use of soil nutrients is usually regarded as exploitation or 'mining' of nutrients leading to degraded soil fertility. However, two different concepts should be distinguished: exploitation vs. utilization. The difference can be compared with pumping water from wells. If a water level is slightly or considerably lowered, water is exploited and the system is not sustainable; if the water level is not or not noticeably lowered, water is 'only' utilized and the system is sustainable.

Synopsis 3: Plant nutrient sources

A. Internal (farm) nutrient sources

- soil (available and reserve nutrients in the rooting zone)
- subsoil and parent material (nutrient reserves)
- legume plants, etc. (N-fixation by crops, green manure, free-living organisms)
- crop residues (nutrients in straw, leaves, roots etc.)
- green manure (for nutrient storage and saving, etc.)
- animal manure (nutrients in stable manure or sludge)
- compost, ashes, etc. (organic or mineral nutrients)

B. External nutrient sources (from farm surroundings)

- weeds and mud from rivers, lakes, swamps; seaweed
- litter and bark from forest
- organic top soil layer from 'wastelands' (peat, heath, etc.)
- animal manure collected: for burning (ash), biogas, composting
- fodder collected for or by cows and sheep (nutrients utilized as manure)
- other nutrient-containing substances (ashes, insects, etc.)
- atmospheric sources (rain, etc.)

C. Imported nutrient sources (usually bought)

- organic fertilizers from waste products or by-products of plant or animal processing factories
- communal waste products (town compost, sewage sludge)
- mineral fertilizers
- fodder

Exploitation of soil nutrients frequently occurs and decreases the level of available nutrients quickly or slowly, because the degree of continuous mobilization from nutrient reserves is inadequate when compared with (daily) crop nutrient requirements. Farming systems based on *exploitation cropping* will be discussed later on.

Utilization of soil nutrients consists of removing part of the nutrients without significant impoverishment of the nutrient supply or reduction of soil fertility. This practice creates the impression of *permanence* of agricultural production.

The basis of this concept is the relatively high degree of mobilization of some nutrients from the reserves compared with the amount of nutrients required and removed. Soils with a high regenerative capacity (without apparent impoverishment) are rare in the case of primary nutrients. As for secondary or micronutrients, however, this is frequently the case.

Many soils have provided crops for centuries with trace elements without noticeable decrease of their supply. Their mobilization from a comparatively large reserve sufficed to satisfy a relatively small requirement of the harvest, part of it being compensated by some return with crop residues and manure. Many soils will continue to supply a range of nutrients for further decades or even centuries. It would thus not be justified to call this removal an *exploitation*. On the contrary, a fertilization for compensation of such losses would rather be an exploitation of the farmer's purse.

Subsoil or parent material often contains a fresh mineral supply which can be brought into the root zone either by deep ploughing or by mechanical transfer from deep layer material to topsoil (e.g. liming, marl or clay application).

Organic nutrient sources

All kinds of organic matter contain nutrients. They are moderately to slowly released by the mineralization process. The main emphasis of this discussion will be on the nutrient aspects, not on the aspect of humus supply, although also very important.

Crop residues are generally applied directly to the soil, their nutrients being partly available again for the next crop. If they are used via composting or used as fodder, the cycling is longer. The burning of residues, e.g. stubbles and straw, enhances the mobilization of the nutrients, but the nitrogen content is lost into the air.

Green manure increases the working capital of nutrients by additional nutrient mobilization, N-fixation or by saving nutrients from leaching thus reducing losses.

Nitrogen fixation enables a considerable N-input: by legume crops (50 - 200 kg N/ha), by green manure plants (e.g. *Azolla* with *Anabaena* in rice fields up to 400 kg N) and by blue-green algae, although free-living N-fixing organisms are much less effective.

The optimum use (with smallest losses) of farm animal manure can be made by composting (which is, however, a labour-intensive procedure). The use of stable manure with straw is superior to liquid manure (slurry), which is nevertheless increasingly being applied. The amount of manure can be increased by using cows and sheep as nutrient collectors.

Compost is a general term for substances with a wide range of quality, from collected waste products to carefully treated, earthworm-processed 'compost-earth'. A good compost preparation is therefore an efficient method for nutrient management.

If waste products of any kind (industrial or communal) have to be paid for, they must be profitable (comparatively cheap), have a substantial nutrient content, but no detrimental or toxic effects (the latter being a special danger of communal waste products).

In order to protect farm soils from imported toxic heavy metals, as well as from excess of essential heavy metals, some countries have introduced upper limits for such contents, e.g. for town sewage sludge and compost prepared from town waste products. Furthermore, even 'safe' products should only be applied to soils which have not yet reached critical contents of toxic elements with regard to crop uptake.

Organic waste products, if they are to be sold, generally require mechanical and chemical preparation (drying, grinding, mixing, granulation, etc.). Important criteria of organic nutrient sources are the dry matter content, total and quick-acting nitrogen, C/N ratio, etc.

Nutrient sources based on organic matter, have a complex influence on plant growth which can only be presented in a summarized form (Synopsis 4).

Synopsis 4: Effects of organic material on plant growth (via the soil)

\# *Improvement of physical soil properties* (directly or via soil organisms):

- ☐ better soil structure as a result of soil loosening and crumb stabilization
- ☐ better water holding capacity and soil aeration
- ☐ surface protection by mulch layer

\# *Influence on chemical properties:*

- ☐ sorption of nutrients by humic acids
- ☐ supply of nutrients from mineralization or dissolving action on soil minerals
- ☐ fixation of nutrients in organic complexes (mainly a negative effect for a shorter or longer period)
- ☐ effects of growth regulators produced in soil (e.g. negative effects of growth inhibitors or positive effects of antibiotics providing a certain protection against some bacterial diseases)

Mineral fertilizers

The effective use of mineral fertilizers need not be discussed here in detail, but some aspects will be mentioned further on. Future restrictions may result from shortage of raw material, especially of rock phosphate. Most predictions, however, are obsolete because of new deposits or technologies. Furthermore, it should be kept in mind that phosphate is not destroyed but only *used* in agriculture; most of it could be directly recycled or regained from waste waters.

The amounts of nutrients required for crops or crop rotations are either estimated from local experience (generally based on standard crop removal data) or, in a more reliable way, by diagnostic methods. Commonly the soil analysis for available nutrients is used with different extraction methods in different countries. The amount of fertilizer nutrients to be applied results from the difference between actual and required levels of available nutrients. With a different concept and for many cases, the plant analysis (e.g. leaf analysis) gives more precise information. Diagnostic procedures are described in textbooks on fertilization.

NUTRIENT CYCLING IN CROPPING AND FARMING SYSTEMS

Whereas nutrient balances represent a static concept, nutrient cycling involves a different and much wider concept. Nutrient fluxes move in many directions and with different intensity. They could also be considered as a 'fertility transfer', which can be intentional by the farmer or self-acting by natural processes. Classical examples are the phosphate accumulation in archaeological dwelling sites (used for detecting them) or the nutrient transfer from grassland to arable fields (proverb: grassland is the 'mother', the 'nutrient provider' of arable land).

The internal cycle of nutrients, within the field or farm, is of special importance and should be used efficiently as well as carefully protected against avoidable losses. External cycling includes the nutrient exchange with the adjacent environmental area and the nutrient export or import. Costly inputs should be restricted to the minimum of requirements. By quantifying the cycling streams (fluxes) it is possible to produce nutrient balances for specific smaller or bigger areas.

Cycling of nutrients and nutrient sources does occur on different scales and with different means of transport:

- on fields: from soil rooting zone to crops (and *vice versa*);
- in farm area: from grassland to arable land; from nutrient-rich areas to poor soils, from hilltop to small depressions (along the slope gradient);
- in village area and landscape units: from surrounding forests or wasteland to fields (gathering of food or fodder nutrients); from mountains or hills to valleys by soil erosion;
- in countries from farm land to town area (food, etc.) and *vice versa*, return of industrial and communal waste products to arable land.

In the case of big cities (megapolis) the recycling of imported nutrients to the farm area is rather limited. Many waste products are rather deposited into landfills or led into rivers or the sea (after 'biological' treatment, but without extracting phosphate, etc.).

Synopsis 5: Cycles, input and output of nutrients (at farm level)

Cycling of nutrients (working capital)

- from soils to plants (crops, green manure, weeds)
- from plant residues to soil
- from grazing land or fodder crops to animals
- from animals (via excretions) to soil (directly or via farm manure, slurry)
- from fields to farm (food for humans, fodder for animals)
- from farm to fields (manures, farm wastes, compost)

Input from:

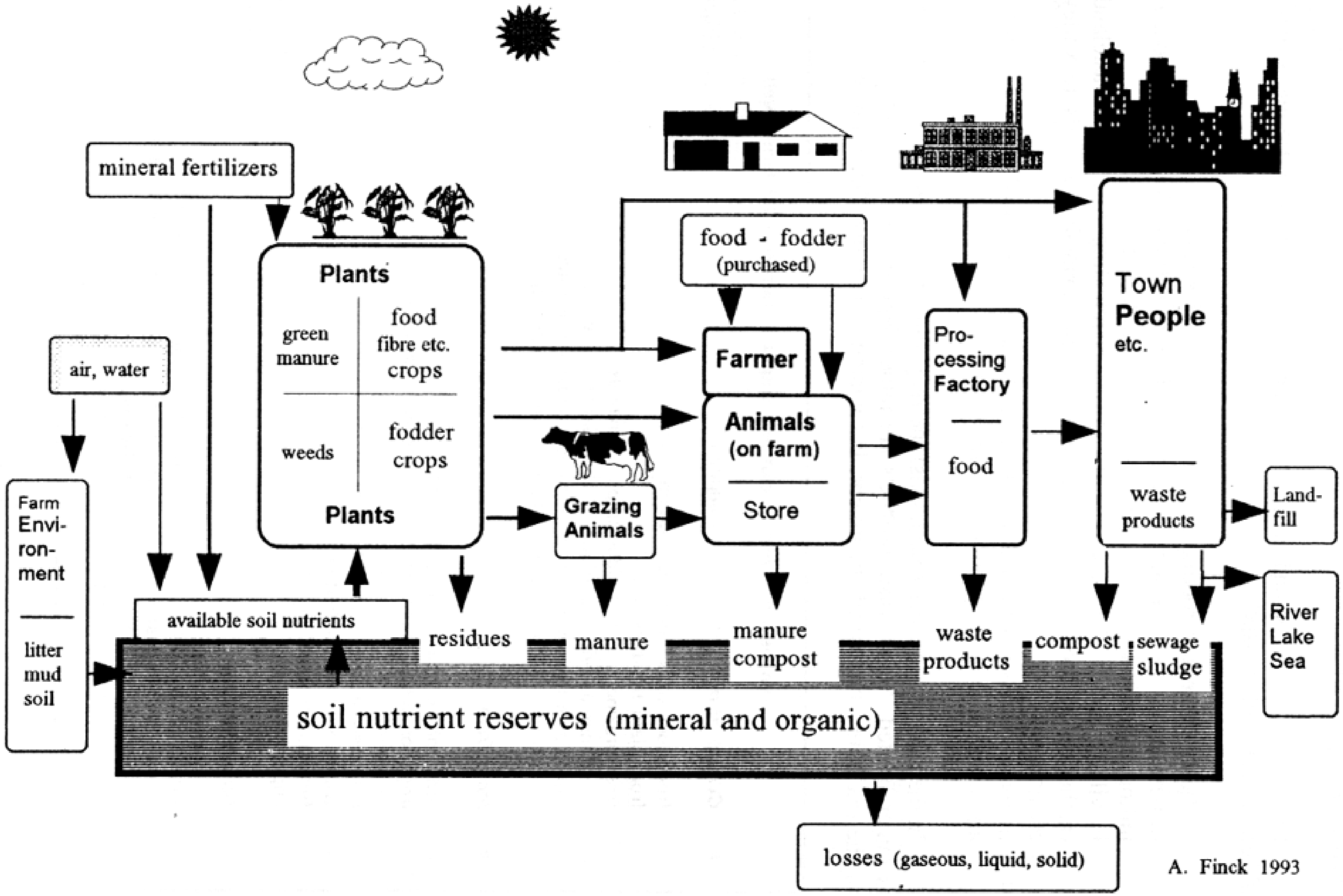
- atmosphere (rain, dust, pollutants)
- irrigation water (salts, solids), surface and subsurface water
- N-fixation
- collected products from the farm environment
- waste products (industrial, communal)
- fertilizers (mineral and organic)
- imported fodder

Output or losses:

- export of crop products (food, fodder, raw materials), animal products
- losses
  - * in gaseous form (from soil, manure, fertilizer, burning etc.
  - * by leaching into groundwater, etc.
  - * by other processes (soil erosion, etc.)

Recycling of nutrients within the farm area does not tend to be uniform. For example, slurry is deposited preferably on fields near the farm because of transport costs. A small-scale example of recycling with uneven distribution is the spot-wise deposition of excretions by grazing animals (King, 1990; Haynes and Williams, 1993). This natural procedure is very

FIGURE 1
Nutrient cycling on different scales



A. Finck 1993

inefficient because small areas obtain high rates of nutrients (e.g. equal to 800 kg/ha N, 200 kg/ha P). Unless the excretions are mechanically distributed, substantial amounts of nitrogen are lost, whereas P is accumulated in excess (possibly next to deficient spots). Another example is the uneven distribution of ashes due to the burning of straw after it has been accumulated for this purpose in rows or spots.

None of the cycles is closed, most of them are leaking. Some losses are unavoidable (natural load) whereas others are avoidable by adequate nutrient management. A common opinion claims that decreasing N-fertilization is the best preventive measure for reducing leaching losses of nitrate. This is, however, only partly true since an additional fertilization with minimum-factor nutrients can be much more effective. As a compensation for losses a certain replacement is mostly required (nutrient supplementation).

Cycling is a very complex system. Although it is not so difficult to design a complex model of nutrient fluxes, their quantitative assessment will have to be based partly on some more or less uncertain estimates. The result, therefore, can only be approximative. For practical use, cycling models should be restricted to the important nutrient fluxes, as illustrated in Figure 1.

MANAGEMENT OF NUTRIENTS IN CROP ROTATIONS

Rules for the management of nutrients for special crops are rather well known and need therefore not be discussed in detail. Since monocultures are the exception, however, the farmer usually has to consider the nutrient supply of rotations.

Rotations are planned for several (and partly competing) reasons: for products wanted, general crop requirements, maintenance of soil fertility, plant disease and pest control, nutritional supply, etc. Furthermore, rotations in countries with food shortage are different from those in areas of overproduction.

From the crop nutrition point of view, different aspects are to be considered. Rotations can consist of crops with high or low nutrient requirements or of crops known to either improve or rather decrease soil structure and activity of soil life. Other reasons for special crop sequences could be the best use of nutrients mobilized by previous crops or of the nutrient carry-over to the following crop. The well known example of legumes alternating with not N-fixing crops should also be mentioned. Rotations may be chosen that do not leave the soil without green cover (intermediate crops, green manure or even weeds) in order to prevent nutrient losses from bare fallow in the period with pronounced leaching. Better use of nutrients can also be made by placement of nutrients (e.g. more for crops, less for weeds) or by crop combinations like intercropping, mixed cropping, etc. (Francis, 1989).

Replacement of losses in open cycles is essential for the maintenance of the production potential (soil fertility). The aim is a continuous stable crop sequence with balanced nutrient supplies and maintenance of soil fertility.

Stress resistance of crops

The usual concept of nutrient supply is based on 'normal' growth conditions. In fact, however, there are frequently constraints for crop growth under stress conditions:

Synopsis 6: Possible improvement of nutrient management

Aspects of crops:

- crop sequences according to crop demands and application of available nutrient sources
- choice of crops with extra potential of nutrient mobilization (via mycorrhiza or rhizosphere associated organisms)
- breeding of crops with lower nutrient needs or higher nutrient uptake (higher nutrient efficiency, i.e. stronger mobilization capacity)

Aspects of nutrient source:

- organic manure given to crops with best utilization
- crop sequences with best carry-over use (especially in the case of legumes)
- making full use of crop by-products (straw, etc. as nutrient source)
- adaption of crop rotation to spatial and temporal variation of available nutrient in soils (e.g. immediate use of increased nitrate peak at the start of rainy season)
- preference for crops with good utilization rate of mineral fertilizer nutrients (for N and K more than 50-60 %; for P more than 10-15% , e.g. by placement on deficient soils (resulting in more nutrients for crops, but less for weeds)

Aspects of nutrient losses:

- possibly a permanent vegetation cover on soils (to avoid leaching losses)
- complete plant cover or plant stripes on slopes (to prevent soil erosion)
- low and deep rooting crops (regaining nutrient from subsoil)
- proper weed control (saving nutrients for crops)

- climatic stress (cold, dryness, excess of water, etc.);
- soil-borne stress (soil acidity, soluble salts, toxic metals);
- biotic stress (by diseases, pests);
- environmental stress (by emissions);
- stress due to crop treatment (spraying with fungicides, nutrients, etc.).

The stress situation is often aggravated by a combination of several factors, e.g. low temperature at the time of crop protection spraying.

Resistance of crops against cold stress can be increased by optimizing the supply with some nutrients (K, P, Mn, Cu). Soil-borne stress can be eliminated or at least decreased by soil amelioration, e.g. fixation of toxic substances by increasing the soil reaction and addition of missing nutrients. On soils polluted with heavy metals their fixation can be increased by special amendments.

A balanced nutrient supply (instead of a relative N-surplus) increases the resistance against certain bacteria and fungi, resulting in a lower requirement of plant protective chemicals.

The interaction between nutrient supply and disease resistance, however, is more complex than generally believed. A surplus of N-supply is known to increase the attacks of fungi (e.g. in wheat of *Septoria nodorum*). On the other hand, in some cases the reverse seems to be true (e.g. with higher N-supply there is a better resistance of wheat against *Septoria tritici*).

Nutrient management in rotations with grassland

An adequate nutrient supply of grassland must take into account not only the yield (of milk, meat etc.), but also the health and fertility, e.g. of cows. The nutrient requirements of grassland plants and animals are more or less similar, but they also differ in part. For example, for highly productive milking cows a higher content of P, Mg, Mn, Zn, Cu in the fodder is required than for a high grass yield. In addition, the special requirement of cobalt, selenium or even chromium should be considered, especially in deficient areas, unless mineral supplements are given.

Extensive grassland is often used as a nutrient source for arable lands without compensating all exports and losses. The special recycling of animal excretions on pastures has already been mentioned. If grassland is included in crop rotations, there should not be too much carry-over of such nutrients which may disturb the nutrient balance of fodder.

NUTRIENT MANAGEMENT IN FARMING SYSTEMS

There is a wide variety of land use types and production systems. For the present purpose they will be presented in the following groups:

- systems with small or large rotations of annual crops or perennial crops;
- systems with or without (bare or plant-covered) fallow (special nutrient mobilization processes);
- systems with or without irrigation (special nutrient regime during the wet phase);
- systems with or without farm animals (special farm-internal nutrient cycle);
- crop fields combined with grazing land or permanent pasture (special aspects of grassland nutrition);
- subsistence farming or market-orientated systems with food or industrial crops (high nutrient export);
- single crops vs. multiple-cropping systems (better nutrient efficiency);
- agroforestry (nutrients from different soils layers and recovered from subsoil);
- farming systems based on exploitation of nutrients vs. sustainable ones (with low or high yield level).

All farming systems have their qualifications under special natural or economic conditions. As for nutrient management in different farming systems, many rules are already presented in the previous sections or can be found in books dealing with fertilization. One important goal of farming systems is an integrated nutrient management for good yields and quality as well as for protection of the environment. Some examples will be given in this context on farming systems with nutrient exploitation, with low input systems and with highly productive sustainable systems.

Shifting cultivation (example of exploitation cropping)

Farming systems based on exploitation utilize the available nutrients at the beginning of the cropping rotation until the supply of some nutrients is more or less exhausted. The cropping period is generally short, because nutrient removal and losses result in a substantial yield decrease after a few years.

A typical example is the (standard-type) *Shifting Cultivation* in tropical forest areas (Nye and Greenland, 1960; Sanchez, 1976). After forest clearing and burning, the nutrients of the ash of the trees as well as those accumulated in the forest soil are utilized by several annual crops. Sustainability of these systems can be achieved by long regenerative phases under natural vegetation, provided that no serious soil deterioration takes place during the cropping period. The rate of exploitation can be increased by mobilizing additional nutrients via 'soil burning'. The standard type of shifting cultivation can be improved considerably by the choice of crops, by special management procedures and by supplementing missing nutrients.

Sustainable agriculture (on low to medium yield level)

The concept of *sustainable agriculture* is getting a high priority. It involves the successful management of resources for agriculture to satisfy human needs while maintaining or enhancing the quality of the environment and conserving natural resources (Plucknett, 1990). Obviously, systems of this kind involve complex interactions and require integration (Edwards, 1990).

A prominent concept is known by the acronym *LISA*, i.e. *Low-Input Sustainable Agriculture*. Such farming systems are called *biologic, organic, ecological* or by the general term *'alternative'*. *LISA* is supposed to optimize the management and use of internal production inputs (mainly on-farm nutrient resources) in order to obtain a satisfactory level of sustainable crops yields and profitable returns (Parr *et al.*, 1990). It is in fact a production at a somewhat lower end of the crop response curve.

The main emphasis is on the use of soils nutrients and internal nutrient cycling via organic substances, but much less on supplementation. A complete cycling, of course, is impossible for most farming systems, certainly on a large scale. Some exceptions may occur on small subsistence farms.

Crop production without mineral fertilizers is possible, but mostly only on a low yield level. The claims for producing better food without mineral fertilizers are not at all substantiated (Finck, 1992), neither those of avoiding chemical crop protection (Goring, 1990). Furthermore, it should be pointed out that *ecofarming* is not generally superior (e.g. in view of less water eutrophication). Although a superiority may often hold true per 'unit of land', it rarely does per 'unit of crop product', because a much larger area of land is required for cropping than with conventional farming.

It should be mentioned that many marginal ecosystems are not sustainable precisely because of low input; on the other hand, a high input is required in some ecosystems if one wants to make best use of climatic and soil resources (Miller and Larsen, 1990).

Sustainable agriculture (on high yield level)

Sustainable agriculture is not confined to low-input conditions. The input, however, should be adequate to the goal which could be a medium or even high yield level. Such systems (in contrast to *LISA*) could be called *AISA* (*Adequate-Input Sustainable Agriculture).*

As demonstrated in Western Europe and elsewhere, a high but adequate use of fertilizers results in sustainable production at a high level and yet without significant adverse effects on environment (Finck, 1992). Farming systems of this kind are rather diverse, but have many, and generally well known, similarities in nutrient management.

In most countries the population pressure will not allow a return to old methods like on-farm recycling. Food production can certainly be increased by better nutrient cycling and prevention of losses, but for the food supply of increasing populations a higher input, especially of fertilizers, will be required. In fact, the principles of the modern comprehensive fertilization concept and the basic principles of sustainability will have to be combined. Integrated plant nutrition systems as part of integrated crop production will be a decisive factor for the final goal: a sustainable high and profitable crop production.

WHAT COULD BE DONE AND BY WHOM?

First, there are the scientists concerned with agriculture who produce research data and develop theories. The validity of this information is usually granted. However, some conclusions from experiments are not as reliable as claimed by the authors (e.g. many yield increases attributed to better N-supply are in fact due to other effects, thus over-estimating the required amounts and increasing the avoidable pollution of water). Consequently, the wealth of scientific information on nutrients and fertilization should be critically examined, evaluated and competently summarized before it is presented as practical agriculture.

Second, advisers are supposed to 'translate' the theoretical suggestions into practical 'know-how'. Unfortunately, the information obtained from science is not always precise or really suited for this purpose. Anyhow, advisers have to combine the information available with their own experience and express it in terms of farmers knowledge.

Third, there are the farmers, eager to produce as high crops yields as possible and who, if they care for their land as owner or tenant, want to maintain its production potential for crops and animals. In addition to their own experience, they want intelligible and definite guidelines rather than sophisticated models with plenty of vague components. They know about the difficulties, uncertainties and disappointments of primary production and want competent and relevant aid from scientists or advisers. Most farmers do their best to get along with the information available for sustainable crop production. Besides the farmers there are also entrepreneurs, some of them looking more for quick profit than for sustainability. Legal regulations may improve this situation.

Last, but not least, there is the general public which is more and more represented by town people. Most of them live rather distant from agriculture and are hardly aware of biological and chemical crop production principles. These consumers demand plenty, good and cheap food, pure drinking water, etc. They try to impose on the farmers their ideas on nature, landscape and farming as well as their demands on town waste recycling. There should be limits to this, because many deplorable developments in agriculture are the result of consumers' pressure. They should realize that farming has its own rules and that high soil productivity is a man-made valuable property that should be sustained for generations to come, especially by proper plant nutrient management. The world population can be fed in much higher numbers than today, but the pollution problems will set stricter limits.

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SESSION 2

Soil organic matter, biomass, soil micro-flora and management of integrated plant nutrition systems

Organic and biological plant nutrient sources: potential, methods for reducing the bulk and improving the availability of nutrients

The phenomenal increase in food production in the country during the last three decades has been the direct result of the use of high-yielding varieties, good quality seeds, fertilizer, irrigation and use of plant protection measures. To sustain the present growth rate in agricultural production, under stresses of changing environment, increasing population, degrading soils and diminishing resources, careful planning and policy decisions supported by scientific data would be warranted.

The food security base of the country is quite narrow as 80% of the total foodgrain procurement is met by three northern states which presently sustain it. However, the yields of wheat and rice have been either stagnating or even declining with decreasing response to inputs such as fertilizer and water. Therefore, there is a need to develop alternative systems to optimize the utilization of natural/biological resources and other inputs to improve economic returns to farmers. The rice-wheat cropping system has become important in northern India, covering about 9 million hectares.

The conventional agriculture largely depends upon high energy inputs and labour saving devices. Although this has helped in increasing the country's food production, there is a growing concern over their degrading effect on soil and environment as well as on the stability of food production per unit area per unit time. The major emphasis should, therefore, be not merely on optimizing crop yields but also on sustenance of the agricultural resource base and improvement of the environmental quality by developing IPNS technologies involving mineral fertilizers, organic manures and biofertilizers/microbial inoculants for different cropping systems.

MINERAL FERTILIZER PRODUCTION AND CONSUMPTION - GLOBAL TRENDS

Plant nutrient supply through mineral fertilizers is a common and conventional practice. After the record consumption of 145.6 million tons and 4.3% growth in 1988-89, the consumption of 143.5 million tons during 1989-90 and 137.5 million tons in 1990-91 marked a drop of 4.2% (6 m.t.) and the beginning of a medium-term period of decreasing global fertilizer use (Table 1). It was expected that the world fertilizer consumption would drop further during 1991-92 and 1992-93. The reason for this trend appears to be the increasing costs and growing awareness about environment conservation.

PAPER 2.1

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TABLE 1
Trends of total fertilizer (N + P_2O_5 + K_2O) consumption and production in major regions (million tons) (FAO, 1992)

Region	Time period					
	1979-80		1989-90		1990-91	
	Consmpt.	Product.	Consmpt.	Product.	Consmpt.	Product.
World	112 472	118 740	143 507	152 701	137 52	147 897
Asia	28 299	22 816	53 190	42 601	56 403	43 924
India	5 273	3 005	11 607	8 581	12 561	9 082
Europe	32 757	35 633	31 296	32 768	26 087	27 217
All developing countries	34 462	23 964	62 270	48 592	65 048	49 890
All developed countries	78 010	94 776	81 238	104 108	72 472	98 006

During 1990-91, there was a decreasing trend in fertilizer production in the developed countries as compared to the year 1989-90, whereas the fertilizer production has increased over the years in developing countries. The total fertilizer consumption in India during 1979-80 was 5273 million tons, which increased to 11 607 million tons during 1989-90 and further increased to 12 561 million tons during 1990-91. A perusal of data (Table 1) shows that there is a gap in the supply of the required amount of plant nutrients due to higher consumption. It appears that a significant part of the plant nutrients taken up by crops came from natural or renewable resources such as nutrient cycling, organic manures and biofertilizers.

On an individual nutrient basis, the least affected nutrient was phosphate which declined by 1.4% in 1990-91, after a loss of 0.4% in 1989-90. Potash was the most seriously affected with consumption declining by 1.1 and 2.5% in 1989-90 and 1990-91 respectively (FAO, 1992).

Unlike the world fertilizer consumption, the trend in developing countries (Table 1) showed an increase of 4.5% in total fertilizer consumption, 3% for nitrogen, 5.7% for phosphate and 10.9% for potash. The developed countries recorded a drop of 10.8% in total consumption with a small gain for nitrogen (3%) and large losses for phosphate (10%) and potash (15.4%). Most of the Asian countries exhibited an increasing fertilizer consumption pattern.

The world fertilizer consumption is expected to grow from 1990-91 to 1996-97 at approximately 0.9% per annum (Gill, 1992). The individual nutrient demand is expected to grow at a rate of 1% for nitrogen, 0.7% for phosphate and 0.8% for potash. These trends in fertilizer consumption in developed and developing countries once again emphasize the importance of biological and organic nutrient sources.

ORGANIC WASTES AND POTENTIAL

In India organic wastes and residues are recycled to convert them into humus and available forms of plant nutrients. It is well known that organic manures play an important role in maintaining soil health as well as being a source of nutrients for crops (Gaur, 1990a). Apart from providing macro-nutrients such as NPK, organic inputs, through adsorption, also prevent the loss of Ca, Mg and S (Allison, 1973). The micronutrients form water soluble complexes with humus components of the soil organic carbon. Their stability with humus compounds is well established (Relan *et al.*, 1986).

The commonly available organic materials for recycling in agriculture are:

- **Livestock and human wastes**: Cattle-shed wastes, other livestock and human excreta, slaughter-house waste, piggery and poultry waste.
- **Crop residues, tree wastes and aquatic weed**: Cereal residues, sugar cane trash, cotton wastes, oil seed cake, aquatic weed, groundnut husk, etc.
- **Green manures**: Sunnhemp (*Crotalaria juncea*), dhaincha (*Sesbania aculeata*), *S. rostrata, Leucaena leucocephala*, Guar (*Cyamopsis tetragonoloba*), Cowpea (*Vigna sinensis*), etc.
- **Urban and rural wastes**: Rural and urban solid wastes, sewage and sullage, biogas slurry.
- **Agro-industrial wastes**: Press mud, bagasse, coir pith, paper and pulp waste, oil cakes, paddy bran and husk, sawdust, etc.
- **Marine wastes**: Sea weeds, fish meal etc.

These biological wastes such as crop residues, animal and municipal wastes (Table 2) are available in India to the tune of approximately 407, 2018 and 29 million tons respectively (Bhardwaj and Gaur, 1985). The nutrient contents of different organic wastes are given in Table 3. Bovine excreta and crop residues together amount to more than 2 318.54 million tons annually with a total nutrient potential of 5.07, 2.10 and 6.19 million tons of N, P_2O_5 and K_2O respectively (Table 4). It is estimated for cattle and pig slurry and about 1/3 N, 1/2 P_2O_5 and all the K_2O is made available immediately (Gaur *et al.*, 1990). The conversion of this much organic matter to useful manure and its use in crop production should help sustain soil fertility and improve crop productivity. Furthermore this would also create a cleaner and saner environment devoid of pollution.

TABLE 2

Estimation of biological wastes from various sources per year in India (million tons)
(Bhardwaj and Gaur, 1985)

Crop residues	407
Animal wastes	2 018
Municipal wastes	29
Sewage water	3 600

RECYCLING AND COMPOSTING

The nutrients present in animal dung, crop residues and other organic materials can be recycled either by composting or mulching or direct incorporation into the soil. All these approaches are useful in improving soil fertility. However, the most efficient or practical methods of application are to be determined for the wide variety of crops grown and agricultural practices adopted.

TABLE 3

Nutrient content of some organic waste materials, FYM, compost, cakes and residues (Ministry of Finance 1990-1991; FAO 1982a, 1982b)

Category	Source	Nutrient Content (%)		
		N	P_2O_5	K_2O
Animal wastes	Cattle dung	0.3-0.4	0.10-0.15	0.15-0.20
	Cattle urine	0.80	0.01-0.02	0.5-0.70
	Sheep and goat dung (mixed)	0.65	0.5	0.03
	Night soil	1.2-1.5	0.8	0.5
	Human urine	1.0-1.2	0.1-0.2	0.2-0.3
	Leather waste	7.0	0.1	0.2
	Hair and wool waste	12.3	0.1	0.3
Crop residues	Rice straw	0.58	0.23	1.66
	Wheat straw	0.49	0.25	1.28
	Sorghum	0.40	0.23	2.17
	Pearl millet	0.65	0.75	2.50
	Maize	0.59	0.31	1.31
	Total pulses	1.60	0.15	2.00
	Pigeon pea	1.10	0.58	1.28
	Chickpea	1.19	n.a.	1.25
	Sugarcane	0.35	0.04	0.50
	Oilseeds	-	-	-
FYM/compost	Farmyard manure	0.5-1.0	0.15-0.20	0.5-0.6
	Poultry manure	2.87	2.90	2.35
	Town compost	1.5-2.0	1.0	1.5
	Rural compost	0.5-1.0	0.2	0.5
	Water hyacinth compost	2.0	1.0	2.3
Oil cakes	Castor	5.5-5.8	1.8	1.0
	Coconut	3.0-3.2	1.8	1.7
	Cotton seed	3.9 (6.5)*	1.8 (2.8)*	1.6 (2.1)*
	Groundnut	4.5 (7.8)*	1.7 (1.7)*	1.5 (1.4)*
	Karanj *(Pongamia pinnata)*	3.9-4.0	0.9-1.0	1.3
	Neem *(Azadirachta indica)*	5.2	1.0	1.4
	Niger	4.8	1.8	1.3
	Mahua Butter tree *(Bassia latifolia)*	2.5-2.6	0.8	1.8
	Rapeseed	5.1	1.8	1.0
	Linseed	5.5	1.4	1.2
	Safflower	4.8 (7.8)*	1.4 (2.2)*	1.2 (2.0)*
	Sesame	6.2	2.0	1.2
Animal meals	Blood	10-12	1.2	1.0
	Meat	10.5	2.5	0.5
	Horn and hoof	13.0	0.3-1.5	-
	Raw bone	3-4	20-25	-
	Steamed bone	1-2	25-30	-
	Fish	4-10	3-9	1.8

* Figures in brackets are decorticated material.

TABLE 4

Nutrient potential of bovine excreta and major crop residues

Sources	Nutrient potential (million tons)		
	N	P_2O_5	K_2O
Fresh cattle excreta + urine	3.442	1.307	2.214
Crop residues	1.630	0.800	3.980
Total NPK	5.072	2.107	6.194

ENRICHMENT FOR INCREASING NUTRIENT AVAILABILITY

It takes approximately six months to obtain a good and mature compost of agricultural residues, which are rich in cellulose, hemicellulose and lignin. Therefore, the necessity for compost activators or inoculants exists. Any substance, or a microbial inoculant, which increases the rate of microbiological decomposition in a compost heap serves the purpose of activator or accelerator. It reduces the time period of composting resulting in production of large quantities of compost in a short time and space.

Organic manures are bulky and have a low nutrient content. Nutrient contents and their availability from compost are enhanced through enrichment techniques. The role of chemical N activators in composting of wide C/N ratio agricultural residues is well known (Gaur, 1982). Farm wastes poor in nitrogen such as straw, dry leaves, corn cobs, dry weeds etc. can be composted in less time by supplementing with chemical nitrogen. Mixtures of agricultural residues with water hyacinth, leguminous residues etc. can be composted without external inputs of an inorganic nitrogen source. Addition of nitrogenous mineral fertilizers as compost activators is uneconomical in developing countries and under anaerobic conditions may result in losses of nitrogen through the process of leaching, volatilization and denitrification.

Inoculation of composts with cellulolytic and lignolytic microbes hastens the composting (Gaur, 1987; Gaur and Mathur, 1990). Efficient strains of bio-inoculants for composting have been isolated (Bhardwaj and Gaur, 1985; Gaur *et al.*, 1982; Kapoor *et al.*, 1978). The most efficient cellulolytic cultures used as compost inoculants for composting of various organic wastes like paddy straw, jamun leaves, sorghum stalk, *Leucaena leucocephala*, banana leaves, etc. are homogenized fungal cultures such as *Trichurus spiralis, Paecilomyces fusisporus, Trichoderma viride* and *Aspergillus* sp.

The chopped crop residues (5-6 cm) were inoculated with the above mentioned inoculants at 300 gm/ton of homogenized culture in 1 m^3 cemented pits. Moisture at 100% was maintained initially and rock phosphate at the rate of 1-2% was added to narrow down C/P ratio. Composting mass was aerated by turning it upside down after fifteen days interval. After 8-10 weeks a good quality compost from paddy straw having around 1.7% N and C/N ratio of 12.3 was obtained (Table 5). The beneficial effect of cellulolytic fungi in composting of dairy farm wastes has been reported (Tiwari *et al.*, 1989a). They also reported the beneficial effect of 10% cattle dung as inoculant and 2% rock phosphate in composting of wool waste containing 66.9% organic carbon and 5.6% N. The final product was obtained after ten weeks of composting. It contained 20.6% organic carbon and 10.0% N with a C/N ratio of 2:1 (Tiwari *et al.*, 1989b). Use of cellulolytic inoculants resulted in reduction of compost bulk, increased total N and hastening of composting (8-10 weeks).

Similar observations have been recorded with mixed crop residues, sugar cane trash etc. at Hissar, Ranchi and Pune. This clearly indicates the potential of these cultures for rapid composting of dry and wide C/N ratio organic materials.

BIO-INOCULANTS FOR THE ENRICHMENT OF COMPOST

By using nitrogen-fixing bacteria and P-solubilizing fungi the nutrient content of compost can be further improved. Studies conducted by use of efficient microbial inoculants e.g.

TABLE 5

Role of efficient cellulolytic fungi as inoculant in preparation of compost from agricultural residues (IAR, New Delhi and other centres)

Location	Substrate	Organic carbon %		Total Nitrogen %		C/N Ratio	
		Without Inoc.	With Inoc.	Without Inoc.	With Inoc.	Without Inoc.	With Inoc.
New Delhi	Sorghum Stalk + Wheat Straw	28.2	23.6	1.41	1.65	20.0	14.3
New Delhi	Jamun leaves	29.5	24.6	1.41	1.56	20.4	15.7
New Delhi	Paddy straw	27.5	24.6	1.15	1.30	23.9	18.9
New Delhi	Paddy straw	23.6	21.6	1.52	1.76	15.5	12.3
New Delhi	Paddy straw + *Leucaena*	25.6	24.6	1.47	1.51	17.4	16.8
Ranchi	Wheat straw + Water hyacinth	28.4	25.4	1.00	1.37	28.4	18.6
Kanpur	Dairy farm waste	12.6	10.4	0.57	0.63	22.1	16.6
Hissar	Mixed crop residues	32.9	30.8	1.38	1.52	24.0	20.0
Pune	Sugar cane trash	38.4	37.0	0.98	1.54	35.0	24.0

TABLE 6

Preparation of enriched compost* with *Azotobacter* and phosphate solubilizer

Location	Substrate	Carbon (%)	Nitrogen %	C/N ratio	Humus	Av. P_2O_5 (ppm)
IARI	Wheat straw + Jowar stalk	21.9 (28.5)	1.82 (1.38)	12.0 (20.6)	9.30 (7.8)	-
IARI	Paddy straw	21.2 (23.6)	1.82 (1.52)	11.6 (15.5)	15.2 (10.2)	36.4* (13.6)
IARI	Paddy straw + Subabul (4:1)	22.6 (25.8)	1.85 (1.16)	12.2 (22.2)	21.1 (16.8)	40.1*
IARI	Chopped paddy straw	23.7 (26.9)	1.78 (1.30)	13.3 (20.0)	-	308.0** (152.0)
IARI	Unchopped paddy straw	26.6 (31.8)	1.72 (1.26)	15.5 (25.2)	-	289.0** (139.0)
IARI	Banana leaf	32.6 (36.8)	2.80 (1.90)	11.6 (19.3)	-	310.0** (314.0)
Kanpur	Dairy farm waste	9.9 (12.2)	0.64 (0.678)	15.46 (20.10)	-	-
Pune	Sugar cane trash	34.5 (36.0)	1.34 (1.08)	26.0 (33.0)	9.7 (6.1)	-

* After 3 months (enrichment done after 1 month of composting)

** Sodium bicarbonate extracted P_2O_5

Figures in parenthesis represent control.

TABLE 7
Effect of rock phosphate and bacterial inoculants on enrichment of urban compost*

Treatment	Carbon %	N %	C/N ratio	Humus %
Compost	15.1	0.84	18.0	3.36
Compost + rock phosphate (RP)	13.3	0.95	14.0	4.20
Compost + RP + *Azotobacter* (Az)	16.8	1.06	15.8	4.48
Compost + RP + Az + *B. polymyxa*	18.2	1.18	15.4	4.32
Initial compost	17.9	0.78	22.9	3.20

* Samples after 2 months of composting.

TABLE 8
Enrichment of urban compost by sewage sludge*

Treatment	Carbon %	Nitrogen %	C/N ratio
Compost (20 tons) + Sewage sludge (10 tons) + rock phosphate (RP)	11.3	1.42	8.0
Compost (20 tons) + Sewage sludge (10 tons)	11.2	1.29	8.7
Compost (20 tons) + RP (200 kg)	11.3	0.82	13.8
Initial compost sample	12.4	0.60	20.0

* Sampling after 6 weeks of composting.

Azotobacter chroococcum (N-fixer) and *Aspergillus awamori* (P-solubilizing fungi) along with mineral N (to lower the C/N ratio) and rock phosphate showed the production of compost rich in nitrogen (1.8%) and available P_2O_5 (Table 6). The humus content was also significantly higher in material treated with microbial inoculants.

The quality of dairy farm waste compost was improved by inoculation with *Azotobacter* and *Aspergillus awamori* (Tiwari *et al.*, 1989a). Sugar cane trash compost containing 1.34% N and C/N ratio 26 was obtained with the bio-inoculants. In the case of chopped straw, compost with 1.78% N and C/N ratio 13.3 was produced with inoculants as against 1.30% N and C/N ratio 20 achieved without bio-inoculants. Banana leaf compost contained 2.8% N and a C/N ratio of 11.6 against 1.90% N and C/N ratio of 19.3 in the control treatment.

The enrichment technology was also found to be effective in improving the quality of urban compost prepared at mechanical compost plants (Gaur, 1983). Highest nitrogen gains were recorded with combined inoculation of *Azotobacter chroococcum* and *B. polymxa* in rock phosphate amended compost (Table 7). The quality of urban compost can be improved by blending it with sewage sludge in a ratio of 2:1 (Gaur, 1983). The N content of the blended urban compost with and without rock phosphate (Table 8) was augmented to 1.42 and 1.29% as compared to urban compost alone (0.60% N).

RELEASE OF PLANT NUTRIENTS

Mineralization of crop residues exerted a favourable effect on the release of plant nutrients. *Sesbania* released the maximum available form of N, S and P while cereal straw caused the immobilization of phosphorus and nitrogen at the same intervals. In general, in all the soils studied, there was immobilization of phosphorus and nitrogen at the same intervals., There was immobilization of nitrogen during decomposition of cereal straw in soil unless C/N ratio was lowered. However, with FYM/compost no such negative effect was observed (Bhardwaj and Gaur, 1985).

Crop residues (cereals and legumes) added to soil increase the soil organic matter status and nitrogen content as well as the cation exchange capacity of the soils. Availability of nitrogen from cereal residues can be increased by the addition of non-edible cakes (Gaur *et al.*, 1973) and rock phosphate which hastens the decomposition rate and increases phosphorus content in soil.

EFFECT OF ORGANIC MANURES ON CROP YIELDS

Numerous experiments have been carried out to study the response of crops to organic manures. The favourable effects of organic manures on the crop yields have been reported by several workers (Gaur *et al.*, 1990; Leelavathi *et al.*, 1986; Sharma *et al.*, 1991). These workers have emphasized that the magnitude of response depends on the type of manure, it's quality, time of application, dosage per unit area, soil characteristics and moisture required during the crop growth season. Summarized yield responses to 12.6 t FYM or compost/ha are given in Table 9. Average response recorded for different crops such as rice, wheat (irrigated), wheat (rainfed), cotton (irrigated) and cotton (rainfed) was found to be 168, 202, 85, 56.4 and 16.2 kg/ha respectively. The response of sugar cane to 25 t FYM/ha was found to be 8 tons cane/ha.

Seven years of trials with potato showed that tuber yield was 30 t/ha when the potato crop received 30 t FYM/ha as compared to 28 t/ha when no FYM was applied in the rotation (Sharma *et al.*, 1991). The residual effect of FYM on the productivity of the succeeding wheat crop was 300 kg grain/ha.

From Table 10 it is clear that application of 5 tons wheat straw/ha increased the pod yield of groundnut by 95.5% and grain yield of the following wheat crop by 17.1%. Nitrogen uptake by groundnut crop in straw amended plots was 100% more than in the control (Gaur and Mukherjee, 1979).

In the black clay soil at Pune, 5 tons sugar cane trash/ha increased wheat yields by 307 kg/ha (12.5%) as an average over N levels in three years (Table 10). Wheat yields of 3 t/ha could be obtained either by applying 120 kg N/ha through fertilizer or 60 kg N/ha through fertilizer and 2.5-5.0 t of sugarcane trash in red loam soils, wheat yield of 3 t/ha was obtained only by using 100 kg fertilizer N/ha along with 5 t/ha of rice straw + water hyacinth. In terms of wheat productivity 100 kg fertilizer N was on par with 50 kg N + 2.5 t of the above organic material and 100 kg N + 2.5 t organic material was on par with 50 kg fertilizer N + 5 t of rice straw plus water hyacinth.

TABLE 9
Response of different crops to compost/farmyard manure (Gaur *et al.*, 1990)

Crop	Number of stations	Number of experiments	Units	Min.	Max.	Average
Rice	63	34	kg paddy/ha	100	216	168
Wheat (irrigated)	31	210	kg grain/ha	82	296	202
Wheat (unirrigated)	14	71	kg grain/ha	74	140	85
Sugar cane*	19	258	t cane/ha	3.7	11.7	8.0
Cotton (irrigated)	10	71	kg lint/ha	48.7	96.1	56.4
Cotton (unirrigated)	25	294	kg lint/ha	11.8	22.3	16.2

* FYM to sugar cane added at 25 t/ha.

TABLE 10
Effect of some organic resources on crops

Crop	Treatment		Control yield (kg/ha)	% increase due to treatment	Reference
	Material	t/ha			
Groundnut	Wheat straw	5.0	1684	95.50	Gaur and Mukherjee (1979)
Wheat	Residual	-	3800	17.10	Gaur and Mukherjee (1979)
Wheat	Rice straw	120 kg N/ha*	6210**	1.00	
	Rice straw + PSM	120 kg N/ha*	6210**	2.90	Gaur *et al.* (1980)
Wheat	Maize stubble	120 kg N/ha*	4970**	26.60	
	Maize stubble + PSM	120 kg N/ha*		35.20	Gaur *et al.* (1980)
Wheat	Sugar cane trash	5.0	2455	12.50	
Wheat	Rice straw + Water hyacinth	5.0	1599	37.87	Bhardwaj and Gaur (1985)

PSM = P solubilizing micro-organism
* 120 kg N/ha inputs is from rice straw + fertilizer N. Rock P also added
** Control here is 120 kg N through fertilizer and rock-P also added.

EFFECT OF ENRICHED COMPOST WITH NITROGEN FIXERS AND PHOSPHATE SOLUBILIZER ON CROP YIELDS

In situ composting is also affected by inoculation with cellulolytic fungi and free-living diazotrophs. The associative effect of cellulolytic fungi, such as *Aspergillus awamori* and *A. niger* with the diazotroph *Azospirillum lipoferum* on soils amended with rice straw gave significantly higher grain and straw yield and nitrogen uptake by the wheat crop than did the uninoculated treatment. Among the compost inoculants *A. awamori* was superior to *A. niger* and *Azospirillum lipoferum*. Combined inoculation of *Aspergillus awamori* and *Azospirillum lipoferum* gave maximum yields. The maximum benefit was obtained with combined inoculation of *A. awamori* and *A. lipoferum* followed by *A. awamori* alone on grain yield and only combined inoculations on N-uptake by the crop (Darmwal and Gaur, 1988).

TABLE 11

Manurial status of enriched compost versus ordinary compost (ICAR Coordinated Project on microbiological decomposition and recycling of organic wastes, New Delhi (Report 1985-86))

Manurial Treatment	Location							
	Hisar		Pune		Kanpur		Kalyani	
	OC	EC	OC	EC	OC	EC	OC	EC
Carbon %	35.1	33.1	35.7	23.7	36.7	26.9	31.9	30.3
Nitrogen %	1.37	1.63	0.67	1.25	0.92	1.36	0.97	1.82
C/N ratio	25.6	20.3	53.3	19.0	40.0	22.0	33.0	16.0
Citrate soluble P (ppm)	115	219	220	270	-	-	940	1400

OC: Ordinary compost EC: Enriched compost

TABLE 12

Effect of enriched compost, ordinary compost and chemical fertilizers on crop yields (ICAR Coordinated Project on microbiological decomposition and recycling of organic wastes (Report 1985-86))

Treatment/location	Yield (kg/ha)			
	Wheat grain			Potato tubers
	Hisar	Pune	Kanpur	Kalyani
Control	1650	2803	1405	-
Ordinary compost (OC)	2100	2524	2505	12702
Enriched compost (EC)	2670	2968	2945	12912
OC + 50% NPK	3460	3508	3440	20330
EC + 50% NPK	3920	4313	4000	22560
50% NPK	3080	3860	3210	17334
100% NPK	4690	4355	4105	22165
C.D. (5%)	210	405	344	4470

TABLE 13

Effect of different organic manures and chemical fertilizers on the yield of crops in acid red loam soil (Birsa Agricultural University, Ranchi)

Treatment	Crop Yield (Kg/ha)		
	Direct effect		Residual effect
	Wheat grain (1984-85)	Groundnut Pod (1985)	Wheat grain (1985-86)
Control (no input)	1283	823	1150
Ordinary compost (OC)	1406	880	1220
Enriched compost (EC)	1660	1293	1850
Farmyard manure (FYM)	1527	1055	1326
Biogas slurry (BS)	1500	1029	1285
OC + 50% NPK	1848	1109	2000
EC + 50% NPK	2113	1577	2596
FYM = 50% NPK	2110	1251	2416
BS + 50% NPK	1933	1276	2300
50% NPK	2160	963	2166
100% NPK	2731	1504	3513
C.D. (5%)	209	102	158

TABLE 14

Effect of enriched* rice straw compost on the grain and straw yields of the wheat crop (C.A. University of Agriculture, Kanpur)

Treatment	Grain yield kg/ha	% increase over control	Straw yield kg/ha
Control	1753	-	3067
Chopped Straw compost	2486	41.8	4440
$N_{60}P_{30}K_{30}$	3080	75.9	5778
Chopped Straw compost + $N_{60}P_{30}K_{30}$	3995	127.9	7532
Unchopped Straw compost	2400	36.9	3711
Unchopped Straw compost + $N_{60}P_{30}K_{30}$	3888	121.8	6844
$N_{120}P_{60}K_{60}$	4520	157.8	7530
C.D. at 5%	620		

* Enriched with rock phosphate and microbial inoculation.

Enriched compost from sugar cane trash prepared with rock phosphate plus bio-inoculants gave the highest number of nodules, nitrogenase activity, grain and straw yields of green gram (Yadav *et al.*, 1992).

Evaluation of the agronomic value of the enriched compost was done by using it in field experiments either alone or in combination with chemical fertilizers. Compost at the rate of 10 tons/ha was applied to the field before crop sowing. The data on the manurial status and crop yields from Hisar, Pune, Kanpur, Ranchi and Kalyani supported the fact that enriched compost had better manurial quality than the ordinary compost (Table 11). Significant differences in crop yields were observed at each location (Table 12).

Field experiments conducted at Ranchi Centre to evaluate effectiveness of enriched compost in comparison with FYM and biogas slurry showed that enriched compost was the most effective either when it is applied alone or in combination with chemical fertilizers. (Table 13).

The field trial conducted at Kanpur on the effect of enriched straw compost prepared from chopped and unchopped material on the yield of wheat crop showed that the grain yield increased by 41.8%. (Table 14).

Crop residues can be directly used as soil mulches or by *in situ* incorporation in the soil. A comprehensive study conducted in different agroclimatic conditions showed the beneficial effect of mulching on various crops in terms of nitrogen uptake and increase in yield. Mulching was found to improve soil microflora and conservation of moisture (Bhardwaj and Gaur, 1985).

SOURCES OF MICRONUTRIENTS

The micronutrient deficiencies can be overcome by application of FYM containing 1020 ppm of iron and 22 ppm of Zn (Maskina *et al.*, 1988). Organic manures also mobilize the native micronutrient through chelation and increase their availability. Long-term experiments revealed that 12.5 t/ha of FYM and 2.5 t/ha of pig and poultry manure were as efficient as $ZnSO_4$ in increasing the grain yield of maize (Table 15) (Nayyar *et al.*, 1990).

TABLE 15

Effect of long-term application of Zn and organic manures on the grain yields (t/ha) of maize and wheat (average of six crops) (Nayyar *et al.*, 1990)

Treatments	Maize	Wheat
Control	2.94	4.26
$ZnSo_4$ (11.2 kg/ha)	3.35	4.44
Farmyard manure		
@ 6 t/ha	3.00	4.35
@ 12.0 t/ha	3.49	4.46
Poultry manure		
@ 2.5 t/ha	2.97	4.30
@ 5 t/ha	3.41	4.49
Piggery manure		
@ 2.5 t/ha	3.30	4.48
@5.0 t/ha	3.09	4.50

MICROBIAL TOXINS, PATHOGENS AND HAZARDOUS PRODUCTS

The production of microbial toxins is high during initial decomposition stages but subsides after stabilization (humification, mineralization stages).

Anaerobic processes are characterized by high levels of toxicity. If the substrates are characterized by very low C/N ratio (animal wastes) ammonia production is the problem. Sometimes phenols and fatty acids also are responsible for toxicity. Anaerobic biodegradation/biomethanation is the most common method of stabilization of sludge. It solves the odour problem.

The pathogens in sludges and animal wastes may be bacteria, viruses, helminths, fungi or protozoa. Bacterial pathogens are *Salmonella typhimurium* present on non-hygienic sludges and manures. Enteroviruses *Coxsacpievirus*, Ecovirus as well as *Adenovirus*, Reovirus and virus responsible for hepatitis are also encountered on sludges (Carrington, 1980). Fungal pathogens found on sewage sludges are mainly *Candida* and *Aspergillus* (Golueke, 1983).

Experiments showed that mesophilic anaerobic digestion may remove 98.5% of *Salmonellae* with a 15-day retention time (Pike, 1980). Most of the strains of pathogenic bacteria such as *Staphylococcus aureus, Salmonella typhimurium, Proteus vulgaris* were eliminated in the digested slurries after 21 days.

Non-edible oil cakes contain a high amount of plant nutrients (Mercykutty *et al.*, 1983) but most of these organic sources have a high concentration of alkaloids which inhibit the nitrification process (Rajkumar and Sekhon, 1981). Karanjin (furano flavanoid) is a potent inhibitor.

Excessive application of crop residues having a wide C/N ratio, without providing proper conditions for their decomposition, leads to immobilization of N and hence its deficiency. Furthermore the production of phytotoxic substances results in the lowering of crop yields. Sewage-based organic manures are found to enhance crop yields but pollution with heavy metals and bacterial pathogens are the main constraints. Another constraint is the

TABLE 16
Total and available heavy metals found in sewage sludge (Juwarkar *et al.*, 1992)

Name of City	From	Heavy metals, mg/kg (ppm)						
		Cu	Zn	Mn	Cd	Cr	Ni	Pb
Ahmedabad	Total	535.2	2145.7	215.0	3.5	60.4	32.3	76.8
	available	50.3	201.2	11.5	0.8	-	2.3	8.3
Delhi	Total	440.6	1610.4	195.2	5.5	53.5	815.2	34.5
	available	49.5	216.2	15.0	1.4	-	52.2	6.3
Nagpur	Total	272.5	832.5	242.6	1.5	49.2	14.8	24.3
	available	45.7	70.3	9.2	0.2	-	1.6	3.5
Madras	Total	210.3	935.0	465.2	8.3	38.5	60.5	16.5
	available	17.2	77.2	24.5	1.3	-	2.2	1.9
Jaipur	Total	265.3	1720.0	255.6	7.3	176.2	37.5	66.9
	available	29.1	79.0	26.0	1.4	-	0.3	6.4

formation of volatile fatty acids (acetic and propionic acids) during decomposition of crop residues under waterlogged conditions which may be phytotoxic and result in reduced crop yields (Lynch, 1977). Heavy application of organic manure leads to an imbalance of nutrients and may depress crop yields. Continuous use of manures at heavy levels lead to a build up of trace elements to toxic levels.

HEAVY METAL HAZARDS THROUGH SEWAGE SLUDGE

Sewage sludge used as organic manure from major cities of India was found to have high concentration of heavy metals like cadmium, lead, nickel, chromium, zinc, copper, manganese etc. (Table 16). Some of these metallic ions (copper, zinc, aluminium and manganese) are essential micronutrients when present at low level but at higher concentrations they prove to be toxic. Cadmium, a highly toxic metal, is observed to be in the range of 3.5-8.3 mg/kg of sludge from highly industrialized cities like Jaipur, Madras, Delhi and Ahmedabad. The concentration of lead was found to be least in all sludges. The highest concentration of nickel (191.5-815.2 mg/kg) was found in sludge of Delhi while in other cities it ranged from 11.4 to 60.5 mg/kg. Sludges from Ahmedabad and Delhi contained more copper (400-500 mg/kg) compared to other cities where it was found in the range of 190-280 mg/kg.

Sludges enriched with heavy metals, when applied to soil, are subjected to diverse interactions and get distributed between different fractions. The bio-availability, mobility and chemical activity of heavy metals in soils depends upon the type of soil and the species of heavy metals. Highly acidic soils (pH < 5.0), low CEC and organic matter favour greater availability of heavy metals to plants but high pH, CEC and organic matter content lower the bio-availability of heavy metals. In general plants are excellent barriers to check the translocation of heavy metals from soils to plants through absorption, except for certain accumulating species. Cadmium, a highly toxic element, is not prevented by the soil-plant barrier and thus accumulates in the food chain at high concentrations.

TABLE 17

Common leguminous green manure crops used in India and their nitrogen content (Abrol and Palaniappan, 1987)

Local name	Botanical name	Biomass (t/ha)	Nitrogen % (moist)
Sunnhemp	*Crotalaria juncea*	21.2	0.43
Dhaincha	*Sesbania aculeata*	20.0	0.43
Dhaincha	*Sesbania rostrata*	19.6	-
Pillipesara	*Phaseolus trilobus*	18.3	1.10
Mungbean	*Phaseolus aureus*	8.0	0.53
Cowpea	*Vigna sinensis*	15.0	0.49
Guar	*Cyamopsis tetragonoloba*	20.0	0.34
Senji	*Melilotus alba*	28.6	0.57
Khesari	*Lathyrus sativus*	12.3	0.54

TABLE 18

Effect of application of phosphatic fertilizers and green leaves on rice grain yield (Karuppiah and Thangamuthu, 1986)

Treatment	Grain yield (t/ha)	
	Wet season	Dry season
Control	4.0	4.0
Rock phosphate (50 kg P_2O_5/ha)	4.4	4.9
Superphosphate (50 kg P_2O_5/ha)	5.4	4.2
Green leaf manure (12.5 t/ha)	4.9	4.8
Rock phosphate + Green leaf manure	5.0	5.3
Superphosphate + Green leaf manure	5.9	4.9

Ruminants grazing on acid soils are susceptible to copper toxicity as the acid promotes luxury uptake of copper by the herbage (Venn, 1970).

GREEN MANURING

The commonly used green manuring crops along with their nitrogen status are given in Table 17. The green manure crops when applied improve the properties of the soil. Green manures also increase the fertilizer use efficiency when applied in combination with inorganic fertilizers.

Increased availability of P from rock phosphate applied to rice with green manuring was observed (Table 18). The phosphate was applied as superphosphate or rock phosphate in combination with *Leucaena leucocephala* leaves as green manure. Combination of inorganic fertilizers like super phosphate and rock phosphate with green leaf increased grain yield in rice (Karuppiah and Thangamuthu, 1986).

Among the green manure crops special attention is being given to *Sesbania rostrata* which bears stem nodules in addition to the root nodules. The amount of nitrogen contributed in terms of fertilizer N equivalence ranges from 80 to 120 kg/ha. In a field trial comparing different green manure crops, it was found that *Sesbania rostrata* produced the highest biomass (20-25 tons/ha) and accumulated maximum N (150-220 kg/ha) (Palaniappan and Siddeswaran, 1990).

BIOFERTILIZER

Biofertilizers have been recognized as important inputs in integrated plant nutrition systems (IPNS). In India biofertilizers are used and their contribution to plant nutrition is realized. The use of blue green algae, Azolla (Singh, 1989), legume green manures (Meelu and Morris, 1988) for rice; *Azotobacter* and *Azospirillum* for wheat, millets and vegetable crops; *Rhizobium* for pulses and oil legume crops; phospho-micro-organisms for a variety of crops is reported. The beneficial effect of mycorrihizal fungi, e.g. vesicular arbuscular mycorrihizae and actinomycetes Frankia, has been observed. Pulses and oilseed legumes occupy about 30 million hectares in India. To cover the whole area with *Rhizobium* biofertilizer there would be a need to produce 15 000 tons considering the rate of application at 500 g/ha. For covering 25% of the area, annual requirement is 2750 tons of biofertilizer (Verma and Bhattacharyya, 1992). Present production level is 1000-1200 tons including *Rhizobium, Azotobacter* and *Azospirillum*. The current annual total production capacity is 2685 tons.

In view of the importance of biofertilizers, different agencies have taken up production of biofertilizers for supplementing plant nutrients such as nitrogen and phosphorus. In spite of these efforts, biofertilizers have not yet covered large areas due to some constraints.

Rhizobium-legume symbiosis

The nitrogen fixation capacity of legume-*Rhizobium* symbiosis is harnessed to improve plant nutrition. Large variations in N_2-fixation by *Rhizobium* are reported (40-200 kg N/ha/yr) (Somani and Bhandari, 1990). The average fixation by symbiosis under Indian conditions is estimated to occur at the rate of 50 kg N/ha/crop (Verma and Bhattacharyya, 1990).

Carrier based *Rhizobium* inoculants have been reported to increase the yield of all grain legumes (pulses), some oil-yielding legumes (soybean, groundnut). *Rhizobium* inoculated seeds increased yield by 7-67% under experimental conditions and 10-15% at farmer's field besides residual effect (Verma and Bhattacharyya, 1990). The N uptake by leguminous plants indicated an increase of 21-64 kg N/ha (Patra *et al.*, 1986).

Nitrogen contribution of legume-*Rhizobium* symbiosis by different crops such as pigeon pea, *Vigna* mungo, chickpea, lentil, cowpea and mungbeans are presented in Table 19 (Baldev *et al.*, 1988). The amount of nitrogen fixed varied from 50-168 kg N/ha depending on the type of legume and agroclimatic conditions. *Rhizobium* inoculation was found to increase the grain yield of these crops over control but the responses varied with different locations. The residual effect after harvest of legume crops on wheat and paddy was observed where the yields were increased by 2.4 and 16.3% for wheat and by 7.9 and 13.2% for rice.

A residual soil N benefit of 9-40 kg N/ha was detected in wheat, grown in intercropping with cowpea (Patra, 1990). In upland soils a significant amount of available N is left in the soil by legume-*Rhizobium* symbiosis. The soil N enrichment influences the availability of residual N.

TABLE 19

Nitrogen contribution of legume-*Rhizobium* symbiosis - Indian experience

Crop	Nitrogen fixed (kg ha^{-1})	Agroclimatic region/ Location	Increase in grain yield over control (%)	Residual effect on yield of subsequent crop (kg/ha)	Increase over uninoculated (%)
Pigeon pea	168	U.P. Haryana Hyderabad Maharashtra Bihar	4-19 24-43 No response 8-12 25-42	UI 2075 (Wheat var. Kalyan Sona) I 2416	16.3
Urad bean	50-55	Tamil Nadu Bihar U.P.	4-21 11-29 17-21	UI 2075 (Wheat var. Kalyan Sona) I 2125	2.4
Chick pea	85-110			UI 2515 (Paddy var. IR 8) 1 27-15	7.9
Lentil	90-100	U.P. Punjab Bihar	4-26 No response 5-17	UI 2257 (Paddy var. IR 8) I 27-15	13.2
Cowpea	80-85	Gujarat Tamil Nadu	1-36 No response	-	-
Mungbean	50-55	A.P. Bihar Delhi U.P.	1-17 16-49 13-33 4-15	-	-

Source: Verma and Bhattacharyya (1990).
Baldev *et al.* (1988).

UI : Uninoculated
I : Inoculated

TABLE 20

Effect of *Rhizobium* inoculation on nitrogen content in shoot of groundnut JL-24 at 60 days stage and pod yield (All India Coordinated Research Project on BNF, ICAR 1990-91)

S. No.	Treatments	Nitrogen content (%)	Yield (kg/ha)
1.	Control	1.31	601
2.	*Rhizobium* IGR-40	1.41	729
3.	*Rhizobium* TNAU-14	2.22	833
4.	*Rhizobium* AU-1	2.72	1446
5.	*Rhizobium* NC-92	2.18	810
6.	*Rhizobium* G-8	2.39	1157
	C.D. at 5%	0.011	196

Inoculation with *Rhizobium* increased the pod yield of groundnut JL-4 to an extent of 10% over control (Table 20). Dual inoculation with *Rhizobium* and vesicular arbuscular mycorrhizae (VAM) enhanced the pod yield by 17.6%. Inoculation of groundnut with rhizobial strain TNAU-14 and phosphobacteria gave 51.5% higher yield over control. In field trials, at 100% P level, inoculation of *R. japonicum* plus VAM fungi and *R. japonicum* plus phosphobacteria gave 17.8 and 16.8% increase in yield of soybean over control, while single inoculation with *Rhizobium* alone increased the yield by 14.2% (Source: All India Coordinated Research Project on BNF, ICAR, 1990-91). Inoculation of French bean var. premier with *Rhizobium phaseoli* increased the pod yields by 33%.

It is common to use *Rhizobium* inoculum in combination with other plant nutrients such as small amounts of nitrogen and an optimum dose of phosphatic fertilizer. However, use of VAM or VAM and inert sources of phosphorus, along with phosphorus-solubilizing organisms, helps in reducing the need for manures and fertilizers (Table 21). Significant improvement in crop yield parameters and nitrogen assimilation is recorded when biological sources, mentioned above, are integrated with *Rhizobium* inoculation (Table 22).

TABLE 21

Nitrogen and phosphorus contents of groundnut plants as affected by *Rhizobium* and VAM inoculation (All India Coordinated Research Project on BNF, ICAR 1990-91)

Inoculation	Total N (mg/plant)		Total P (mg/plant)	
VAM fungus	545.0	(50.5)	33.5	(2.7)
Rhizobium	342.0	(28.6)	15.0	(3.8)
VAM + *Rhizobium*	574.7	(81.7)	36.0	(5.3)
Control	306.7	(56.0)	9.6	(1.6)

Figures in brackets refer to the standard deviation.

Nitrogen fixation by symbiotic association of *Frankia* and non-leguminous plants

Inoculation studies conducted at Bangalore (Table 23) using free-living diazotrophs, e.g. *Azotobacter* and non-leguminous actinorrhizal isolates of *Frankia*, enhanced the nodulation and biomass (21.5 g/plant) in *Casuarina* plants (All India Coordinated Research Project on BNF, ICAR 1990-91).

Blue-green algae and azolla

Blue green algae (BGA), the photosynthetic nitrogen fixers are suitable for the rice crop. An all India survey of rice fields showed that only 33% of the soils were found to harbour useful nitrogen fixing blue green algae. The commonly found genera that are used as biofertilizers are *Plectonema, Aulosira, Anabaena, Nostoc, Calothrix* and *Tolypothrix*. The Azolla-*Anabaena* association is also used as a nitrogen source.

Indian studies show that BGA applied at the rate of 10 kg/ha, a week after transplanting of paddy, contributed approximately 20-30 kg/ha per season and a 5-14% increase in grain

TABLE 22

Nitrogen and phosphorus uptake in grains and straw of chickpea as influenced by combined inoculation (Alagawadi and Gaur, 1988)

Treatment	Total N uptake (mg/plant)	Total P uptake (mg/plant)
Control	63.6	6.1
Rhizobium (Rhizo)	95.9	8.4
P. striata (P.s.)	72.3	7.6
Bacillus polymyxa (B.p.)	73.0	7.4
Rhizo + P.s.	101.2	10.1
Rhizo + B.p.	104.4	10.4
$N_{10}RP_{60}$ (10 kg N + 60 kg P_2O_5 (as rock phosphate/ha)	90.0	9.2
Rhizo + $N_{10}RP_{60}$	111.4	10.7
P.s. + $N_{10}RP_{60}$	91.6	9.7
B.p. + $N_{10}RP_{60}$	98.2	10.4
Rhizo + P.s. + $N_{10}RP_{60}$	143.3	14.9
Rhizo + B.P. + $N_{10}RP_{60}$	136.7	14.0
Rhizo + $N_{20}SP_{60}$ (20 kg N + 60 kg P_2O_5 as superphosphate)	149.6	15.6

TABLE 23

Interaction effects of *Frankia* and *Azotobacter* on growth responses of *Casuarina equisetifolia* seedlings

	Treatment	Shoot wt. (g/plant)	Root wt. (g/plant)	Nodule No. (No/Plant)	Nodule wt. (g/plant)
1.	Control	14.2	8.0	0	0.00
2.	N at recommended level	16.0	10.0	0	0.00
3.	*Frankia*	18.0	12.35	2	1.15
4.	*Azotobacter*	15.5	14.5	0	0.00
5.	*Azotobacter + Frankia*	21.5	17.35	5	3.5

TABLE 24

Average paddy yields (kg/ha) due to BGA (10 kg/ha) inoculation on farm trials conducted in two major rice growing states

Treatment	Madhya Pradesh (56 trials)		Tamil Nadu (118 trials)*	
	Grain	% increase	Grain	% increase
0 N : 40 P : 15 K	2410	-	-	-
0 N : 40 P : 15 K + BGA	2820	17.0	-	-
100 N : 50 P : 50 K	-	-	5100	-
100 N : 50 P : 50 K + BGA	-	-	5480	7.2

* Venkataraman and Shanmugasundaram (1992).

TABLE 25

Effect of Azolla on the yield of rice (IR-36)

Treatment	Grain yield (kg/ha)		% increase
30 kg N/ha	3300	(2800)	17.8
60 kg N/ha	3800	(2800)	35.7
Azolla dual unincorporated	3300	(2800)	17.1
Azolla dual incorporated	3500	(2800)	25.0
Azolla basal (green manuring)	3200	(2700)	18.5
Azolla basal + dual cropping (once)	3500	(2700)	29.6
Azolla basal + dual cropping (twice)	3800	(2700)	40.7

Figures in parenthesis are grain yields without a nitrogen application.

yields. From the long-term field trials (1981-91) it is known that efficiency of BGA decreases with increasing dose of nitrogen. The maximum yield was recorded in combination with 20 kg N/ha (Adil and Katre, 1992). Large-scale farm trials, conducted in Tamil Nadu (118) and Madhya Pradesh (56), indicated an increase in yield at 0 level nitrogen in Madhya Pradesh and a 110 kg N/ha in Tamil Nadu by the application of BGA (Table 24).

Though Azolla-*Anabena* biofertilizer is not very popular, it can make a definite contribution (Table 25) to improving the fertility status of rice cropping systems (Singh and Singh, 1992). Bulky nature and lack of an efficient technology are the major constraints in its adoption as a biofertilizer.

TABLE 26
Crop responses to inoculation with *Azospirillum* spp.

Crop	Inoculation	Parameter	% difference in comparison with non-inoculated control	Reference
Rice, wheat, sorghum	*Azospirillum* strains	Yield and dry matter	Variable	Subba Rao (1981)
Finger millets	*A. brasilense*	Grain yield	12.9-30.9	Subba Rao *et al.* (1983)
Pearl millets	*A. brasilense*	Grain yield	10-17	Subba Rao *et al.* (1982)
Wheat, rice, barley oats, sorghum	*A. brasilense*	Grain yield	0-81	Subba Rao (1981) Significant increase obtained with 0-120 kg N/ha
Barley	*A. brasilense*	Grain yield	10-20	Significant response up to 20 kg N/ha Tilak and Dwivedi (1989)
Sorghum	*A. lipoferum*	Total dry matter	6 %	Wani *et al.* (1987)

Azospirillum

Azospirillum is known for its nitrogen fixing ability. It also contributes other factors, such as hormone like substances and siderophores, which increase the productivity of the host plant. *Azospirillum* is being used in India as it has been isolated from the roots and above ground parts of a variety of forage grasses, legumes and grain crops (Kavimandan *et al.*, 1978; Agarwala and Tilak, 1988). A number of field experiments conducted in various agro-ecological zones revealed that the total NPK assimilation by the inoculated plants was higher than the uninoculated plants (Table 26). Inoculation results in yield increases equivalent to those obtainable by an application of 20-40 kg N/ha. Bacterization resulted in yield increases with decreases or no increases in N concentration (Wani *et al.*, 1985, 1988). Yield increases and associated increased N content are attributed to enhanced nitrogen fixation or increased N assimilation by plants (Wani *et al.*, 1985; Negi *et al.*, 1991).

Enhanced nutrient uptake in the order 30-50% was observed in inoculated plants. There was enhanced nitrate uptake due to increase in nitrate reductase activity following inoculation with *Azosopirillum* (Wani *et al.*, 1988). Inoculation of plants with *Azospirillum* may contribute to improved iron nutrition through the production of siderophores (Wani, 1990).

The total dry matter content of the sorghum increased significantly by 6% when the crop was inoculated with *Azospirillum lipoferum* (Wani *et al.*, 1987) under arid conditions. Barley crop field trials, for 3 years under north Indian conditions, showed increased grain yields of 10-20% when incubated with *A. brasilense* (Tilak and Dwivedi, 1989).

Soil nitrogen affects the response to inoculation. In multi-location trials with pearl millet, maximum 20% increase in grain yield due to individual inoculation of *Azospirillum* and *Azotobacter* and 27.2% and 18.198% increase in plant nitrogen uptake due to inoculation of

TABLE 27

Effect of inoculation with phosphate solubilizing micro-organisms on the yield of various crops under field condition (Gaur, 1990b)

Crop	Location	Yield (kg/ha)		% increase	Reference
		Uninoculated	Inoculated		
Rice	Loamy soil, pH 7.8, 12.8 kg P_2O_5 ha^{-1}	2050	2300	12.2	Guar (1990b)
	Kanpur	4866	5303	9.0	Guar *et al.* (1980)
Wheat	Sandy loam alluvial, IARI, Delhi pH = 8.5, 12.2 kg P_2O_5/ha	4786	5584	16.6	Gaur (1990b)
	Saline soil	2600	3275	26.0	Gaur (1990b)
	Loamy soil = 7.8, 12.8 kg P_2O_5/ha	4975	5216	4.8	Gaur *et al.* (1980).
	Sandy loam alluvial	2600 (RP 60)	2800 (RP60 + PSM)	7.6	Gaur (1990b)
Green Gram	Ibid	4.0 (Gram/pot)	6.6 (Gram/pot)	65.0	Bardiya & Gaur (1990) (unpublished)
Chickpea	Loamy soil	2370	2920	23.2	Gaur & Gaind (1992)
Pea	Sandy loam alluvial soil	2073	2536	22.3	Gaur (1990b)
Soybean	Ibid	1050	1786	70.0	Gaur (1985)
Potato	Ibid	2330	37330	60.0	Gaur & Arora (1979) (unpublished)

Azosopirillum and *Azotobacter* respectively were obtained at zero level of nitrogen application (Wani, 1992).

Azotobacter

Biofertilizers being commonly used to augment the crop nutrition also include *Azotobacter,* a free-living aerobic bacterium found in arable soils. Apart from nitrogen, *Azotobacter* contributes some growth promoting substances which improve the crop nutrient status. No correlation between nitrogen fixation capacity and their growth enhancing capability is reported. In general, however, the net increase of 30-40 kg/ha in N uptake is caused by *Azotobacter* inoculations (Shende and Apte, 1982). The bacterium is applied either as a seed noculation or by dipping roots of seedlings in the cell suspension before transplanting. Commercial preparations of this bacterium have been found to be effective for a variety of cereals, vegetables and plantation crops (Bhandari and Somani, 1990).

Field trials with *Azotobacter* cultures were conducted on wheat, maize, sorghum, cotton, potato and mustard crops (Shende, 1987). The effect of the *Azotobacter* culture on yield varied from 0 to 32%. Cultures which are specific for a crop variety are found to be beneficial. *Azotobacter* inoculation experiments show both supplementary and complementary

TABLE 28
Field response of crops to dual inoculation with VAM fungi and nitrogen fixers in India

Crop	Inoculant	Observations	Reference
Soybean	*G. fasciculatum* + *Rhizobium*	Increase in shoot and grain mass and P content non-significant	Bagyaraj *et al.* (1979)
Cowpea	*G. fasciculatum* + *Rhizobium*	Inverse relation between P levels and VAM inoculation	Tilak (1985)
Pigeon pea	*G. fasciculatum* + *Rhizobium*	VAM alone increased significantly during first year of the 3 years observation	Subba Rao (1988a)
Chickpea	*Rhizobium* + *G. versiforme*	Shoot dry matter and P contents significantly increased over control	Singh & Tilak (1989)
Groundnut	*G. fasciculatum* + *Rhizobium*	Dual inoculation significantly increased pod yield over *Rhizobium* inoculation	Subba Rao (1988b)
Tomato	*Glomus fasciculatum* + *Azotobacter vinelandii*	No increase of dual inoculation over *Azotobacter* inoculation	Mohandas (1987)
Tomato	*G. fasciculatum* + *Rhizobium*	No influence on shoot dry mass and N content	Mohandas (1988)
Fodder sorghum	*G. fasciculatum* + *A. brasilense*	Dual inoculation was better than single inoculation. Effect of VAM alone is equivalent to 50 kg P_2O_5/ha applied as single superphosphate	Sreekumar & Tilak (1988)

effects. In a trial on cotton at Surat, application of 200 kg N/ha did not decrease the efficiency of *Azotobacter*. At Babugarh, treatment of potato tubers with *Azotobacter* gave additional increase in yield with different doses of fertilizers up to 200 kg N/ha.

Phosphate solubilizers

Phosphate solubilizing micro-organisms are used as biofertilizer for supplying phosphorus to plants in soils poor to medium in available phosphorus. *Bacillus polymyxa, Pseudomonas striata, Aspergillus awamori* and *Penicillium digitatum* have been reported to be efficient phosphate solubilizers (Gaur, 1990b). A carrier based Microphos biofertilizer containing *Pseudomonas striata* has been successfully tested on different crops. The contributions of phosphate solubilizing cultures in mobilizing insoluble sources of phosphorus for the growth of crop plants are summarized in Table 27.

Vesicular Arbuscular Mycorrhizae (VAM)

The associative effect of mycorrhizae (VAM) and asymbiotic nitrogen fixers is also a mechanism used to increase crop production. The results of field trials conducted in India on the effect of dual inoculation (VAM + Nitrogen fixers) indicated that the combined inoculation is superior to single inoculation in the majority of the trials and that the response varied with soil, plant and the endosymbionts (Table 28). On an average phosphate

TABLE 29

Major plant nutrient elements in worm processed animal wastes

Waste material	Element content (% dry wt.)					
	N	P	K	Ca	Mg	Mn
Separated cattle solids	2.20	0.40	0.90	1.20	0.25	0.02
Separated pig solids	2.60	1.70	1.40	3.40	0.55	0.03
Cattle solids on straw	2.50	0.50	2.50	1.55	0.30	0.05
Pig solids on straw	3.00	1.60	2.40	4.00	0.60	0.05
Duck solids on straw	2.60	2.90	1.70	9.50	1.00	0.10
Chicken solids on shavings	2.75	2.70	2.10	4.80	0.70	0.08

TABLE 30

Vermicomposting of farm residues

Time of sampling	Organic carbon %		Total nitrogen %		C/N ratio		Available P (ppm)	
	Inoc.	Uninoc.	Inoc.	Uninoc.	Inoc.	Uninoc.	Inoc.	Uninoc.
Trial A								
4 weeks	38.8	40.8	1.79	1.28	21.7	31.9	-	-
8 weeks	31.8	39.5	1.68	1.26	18.9	31.3	-	-
Initial raw material								
0 week	51.9		1.12		46.3			
Trial B								
8 weeks	25.2	38.9	0.74	0.47	34.1	82.8	109	93
16 weeks	18.1	26.8	0.85	0.52	21.3	51.3	122	107
Initial raw material								
0 week	48.9		0.38		128.6		-	

solubilizing micro-organisms contribute 30 kg P_2O_5/ha in one season. Efficient cultures of phosphate solubilizers are also used for enriching compost.

Lack of suitable inoculum production technology is a major limitation for commercial exploitation of VAM fungi since they are obligate symbionts.

Vermicomposting

Vermicomposting has proved to be an efficient and inexpensive method of improving nutrient availability. Earthworms can grow on a wide variety of agricultural wastes, including pig and cattle solids and slurries, spent mushroom compost and paper pulp. The gut of earthworm acts as a bioreactor providing idea conditions for the microflora responsible for enzymatic degradation of complex biopolymers. The muscular gizzard of the worms grinds food to small particle size (2-4 micron) thereby increasing the surface area. The castings excreted by the worms are an effective biofertilizer with a high content of readily available minerals and humus for plant growth. The action of worms on the waste material is such that most of the nitrogen is converted to available nitrate enhanced by microbial activity. Similarly, the amount of soluble phosphorus, potassium and magnesium available to plants also appears to be increased. There may however, be some nutrient imbalances resulting from nutrient deficiencies or immobilization but this can easily be corrected by addition of suitable inorganic supplements to produce a balanced growth medium.

Vermicomposting of agricultural wastes at IARA, New Delhi

Two trials were conducted with mixed organic materials. Trial A had more green materials like grasses and *Leucaena* leaves mixed with soil and paper. In trial B, 4 kg of composting material consisting of 2 kg paddy straw, 1 kg soil, 1/2 kg twigs and 1/2 kg shredded paper were laid in layers per pit. The bottom-most layer had twigs to permit percolation of excess moisture. The compost pits were kept moist and waterlogging was prevented. Worms were introduced into the pits at the rate of 100 worms/pit after ten days initial decomposition. The pits were covered with a thin layer of soil. The results show that earthworms were helpful in composting, augmentation of N and lowering of C/N ratio (Table 30). Earthworms were also active in the decomposition of materials with high C/N ratio (trial B). Without worms the C/N ratio attained was 51 but with addition of worms it was narrowed down to 21. The use of worms also enhanced the available phosphorus content of the compost. The combined use of cellulolytic fungi and earthworms showed better performance than either of them alone.

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respective contribution of NH_4^+ and $N0_3^-$ ion in nutrition, depending on the time of application and on the soil-plant interaction, by means of NH_4N0_3 labelled with ^{15}N, the contribution of the two ions NH_4^+ and $N0_3^-$ applied as fertilizers at the time of grain formation was studied.

Thus, from the total of 120 kg N/ha applied half in autumn and half in spring, NH_4^+ accounts for 29% at kernel formation, and 21.8% at straw formation, the general utilization coefficient being 50.8%.

In the same conditions, the nitrate form was more efficient, the utilization coefficient being 34.8% for kernel, 30.8% for straw, the total being 65.6% (Table 5).

The higher contribution of the $N0_3^-$ at the time of grain formation indicated by% Ndff, the utilization coefficient being higher in all cases, may be caused by the higher mobility of this ion. It is known that, in contrast to the NH_4^+ ion, the $N0_3^-$ ion is retained to a much lesser extent by the soil adsorptive complex, circulating in the soil solution by mass flow. The fact that the nitrate moves with the water allows the root system to exploit the nitrate ion better. This can explain the superior values of the utilization coefficient of $N0_3^-$ (Hera *et al.*, 1984).

Some interesting results have been obtained on soybean (Table 6). The only significant yield increases were obtained when the amount of 30 kg N/ha was applied during vegetation period, before flowering. In this case, %Ndff was 3.2% and the utilization coefficient of N was 20.2%. The highest N content in soybean seeds, derived from soil and symbiotic activity was obtained also when 30 kg N/ha was applied before flowering, which means that the symbiotic process of N_2 fixation took place in optimum conditions. When the intensity of symbiotic activity begins to diminish, the application of low rates of nitrogen fertilizer before flowering stage of soybean can lead to significant yield increases (Hera *et al.*, 1984).

Assessment of nutrient availability as a function of different methods of fertilizer application

Among the factors affecting crop production, fertilizer placement plays an important role. A strong argument in favour of this affirmation are the results received from five countries which participated in the first Coordinated Research Programme organized by the Agriculture Unit of the International Atomic Energy Agency on Rice Fertilization (Table 7).

Surface application and hoeing into the surface were equally effective. At all locations, all other treatments were less effective in supplying fertilizer phosphorus to the rice plant (Fried, 1978; IAEA, 1978). This was in spite of the fact that placement at 10 cm depth in the planting hill actually involved placing the fertilizer in the hole in which the rice plant was transplanted, a treatment that most of the participants and observers anticipated would be the most effective treatment. Before the field experiments with ^{32}P labelled superphosphate were performed, the five-year programme with the non-labelled fertilizer had given inconclusive results and the debate concerned the desirability of extending the programme for another five years. In only a one-year experiment with radioactive labelled fertilizers, the participating countries in the programme had answered the questions.

soil organic matter content approaches a steady state, with the annual input of organic matter balancing the annual output. This process, where the increases and decreases in soil organic matter occur simultaneously, is described as turnover, or (for C) as the flux of C through the pool of soil organic C (Jenkinson, 1988a).

Soil organic matter consists of a series of organic products at various stages of decomposition - from virtually undecomposed plant and animal tissues to 'humus', the black-brown material present in all soils, which is largely the end-product of microbial decomposition. Organic matter mainly consists of carbon, hydrogen, oxygen, nitrogen, sulphur and phosphorus, (C, H, O, N, S and P) but most interest usually focuses on C, N, S and P, for which acceptable methods for their determination exist. Organic P presents special analytical difficulties.

There has been an enormous amount of work which has attempted to characterize the components of soil organic matter chemically, and hundreds of organic compounds have been isolated and identified. These include free sugars, amino acids, organic acids and lipids (e.g. Stevenson, 1982). However, the largest component of soil organic matter is polymeric in nature such as polysaccharides (Cheshire, 1979) and peptide chains, which are stabilized by reaction with clay, organic matter or polyvalent metal cations such as Fe or Al (Stevenson, 1982; Jenkinson, 1988a).

Materials such as these are rapidly decomposed by soil micro-organisms when added to soil. However, when present in the humus in intact soil they are remarkably resistant. This is probably because organic matter contains a vast number of classes of molecules, relatively widely spaced, and randomly linked by various condensation reactions. It is much less energetically favourable for a micro-organism to release exocellular enzymes to degrade such materials than to release enzymes to degrade regular polymers such as starch, cellulose or protein.

As the chemical structure of soil organic matter is poorly understood (e.g. Jenkinson, 1988a), any discussion of the reasons for its stability is rather speculative. However, it is certain that a wide range of structures is present in soil organic matter formed by random reactions between molecules, in a quite different way to the formation of biopolymers, under genetic control, by living plants and animals.

The use of acids, alkalis or organic solvents to extract soil organic matter, which is then characterized chemically, has been widespread. However, to date attempts to relate the chemical composition of soil organic matter to, for example, its nutrient-supplying power, (e.g. N mineralization rate) or biological activity (e.g. soil respiration) have been rather unsuccessful (see Powlson, 1990). Nuclear Magnetic Resonance spectroscopy (NMR) is one technique, however, which is developing rapidly and may have considerable future applications. In particular, organic P in soil is difficult to study by traditional chemical methods but ^{31}P NMR of NaOH extracts of both New Zealand and UK soils showed that diester P is a form of P, probably associated with the microbial biomass (Tate and Newman, 1982), that is potentially readily mineralizable and available for plants. Thus, when an old grassland soil from Rothamsted was ploughed and left fallow for 20 years, monoester P (mainly inositol phosphate) changed little but diester P (phospholipids and DNA) declined greatly (Hawkes *et al.*, 1984). NMR also offers the huge potential advantage that solid samples of intact, natural soil may be analysed. It has also been used to identify different forms of organic C in soil including polymethylene chains, polysaccharides, aromatic structures and carboxylic acid groups (e.g. Oades *et al.*, 1987). At present this technique is at an early stage, and the spectra are usually difficult to interpret quantitatively. However, future progress in this direction is anticipated (Powlson, 1990).

The current 'state of the art' is such that current understanding of nutrient dynamics has not arisen from a detailed knowledge of the chemical structure of soil organic matter but rather from studies in which it is regarded as one or more pools of C, N, P or S, without being chemically defined. A clear link between chemical structure and decomposability has not yet generally been made. However, current developments using a range of physico-chemical approaches offer some promise.

It is remarkable, but possibly true, that the current 'state of the art' in soil microbiology is in a similar position. There have been many studies of individual soil micro-organisms grown either *in vitro* or in soil under axeinic conditions. However, in terms of studying soil nutrient dynamics, work with single species, or even a cluster of species of micro-organisms has not been generally useful. Exceptions include mycorrhizae and *Rhizobium* which have very specialized functions. Part of the problem is that so few soil micro-organisms have yet been identified. However, this is not the main reason. Rather the problem resides in the fact that soil microbial activity resulting, for example, in CO_2 evolution, N mineralization or immobilization, is the net result of complex interactions between the many thousands of microbial species and many thousands of organic moeities in soil organic matter. Thus, as with organic matter itself, using a 'black box' approach - measuring the microbial biomass as a single, undifferentiated unit (Jenkinson and Powlson, 1976) - has proved surprisingly useful in studying soil organic matter dynamics. It is hoped to illustrate these concepts further in this paper, being mindful of the development of powerful techniques in molecular biology which will enable the study of the survival and biology of single microbial species in whole soil, with its full suite of organisms intact (e.g. Hirsch *et al.*, 1993). This approach will almost certainly increase our understanding of microbial survival in soil, and of the factors controlling specific processes. However, for ecosystem studies and investigations into nutrient flows that result from large consortia of microbes processing a wide range of substrates, the 'black box' approach, in which the microbial population is treated as an undifferentiated whole, still has much to offer.

MEASURING THE SOIL MICROBIAL BIOMASS

Direct microscopic counting

Microscopic counting is still the most direct method of estimating the amount of microbial biomass in soil, but is technically difficult and completely unsuitable for routine use. Thin films are prepared from an agar-soil suspension, mounted on microscope slides and then treated with an appropriate stain. Phenolic aniline blue is often used as it stains protein and is thus considered to give an estimate of the entire population. The numbers and sizes of spherical organisms and the lengths and diameters of fungal hyphae are measured and converted to total biomass by using conversion factors for specific gravity, percentage carbon content and percentage dry matter, obtained from micro-organisms grown *in vitro*. Other stains, especially fluorescent ones like FITC or acridine orange, are much easier to count but do not stain the full range of organisms. This method is discussed in more detail by Jenkinson *et al.* (1976) and Jenkinson and Ladd (1981).

Fumigation-incubation method

Jenkinson and Powlson (1976) showed that more CO_2 was evolved from a soil fumigated with chloroform, following fumigant removal and aerobic incubation, than from a similar non-fumigated soil. They subsequently showed that this extra CO_2 (the CO_2 flush) came from the microbial cells, killed by $CHCl_3$, as they were decomposed by the subsequent recolonizing population. They suggested that measurement of the CO_2 flush could provide an estimate of the amount of biomass in soil.

The standard method uses soil, first incubated at 40-50% water-holding capacity (WHC) for 7-10 days at 25°C, then given a 24-hour fumigation with *ethanol-free* $CHCl_3$, followed by fumigant removal and a 10-day aerobic incubation of the soil following readjustment to 50% WHC. Biomass C (B_c) is then calculated from: $B_c = F_c/k_c$ where F_c = [(CO_2 - C evolved from the fumigated soil)] minus [(CO_2 - C evolved from the non-fumigated soil)], both over the 10-day period. The constant k_c is taken to be 0.45 under these conditions, on the basis that approximately 45% of the carbon in micro-organisms *added* to soils, followed by fumigation and incubation as described above, is evolved as CO_2 in 10 days. This method has been widely used since its introduction and, provided the soils are first incubated as above, results are in reasonable agreement with measurements obtained by direct microscopy (e.g. Jenkinson *et al.*, 1976; Vance *et al.*, 1987a). Biomass C measurements can be converted to total biomass by assuming that the biomass contains 45% C on a dry weight basis. In the original method samples of coarsely sieved (< 6.25 mm) moist soil, equivalent to about 250 g oven-dry soil, were used. More recently it has been usual to use 2 mm sieved soil in 25-100 g portions (e.g. Ocio and Brookes, 1990b). Jenkinson (1988b) provides a review of this method.

The fumigation-incubation method (FI) cannot be used in soils that have recently been air-dried. Air-drying both kills some of the biomass and renders some non-biomass C decomposable (e.g. Shen *et al.*, 1987). In addition, FI measurements are unreliable in soils which contain much free $CaCO_3$, soils which have recently received fresh substrates (e.g. Martens, 1985), waterlogged soils (Inubushi *et al.*, 1991) or soils with a pH below about 4.5 (e.g. Vance *et al.*, 1987a).

Biomass N can also be estimated similarly by measurement and appropriate calibration of the flush of inorganic N which also occurs during FI.

Fumigation-extraction method

Vance *et al.* (1987b) first showed a close linear relationship between biomass C measured by FI and E_c, where E_c = [(organic C extracted by 0.5 *M* K_2SO_4, from a 24 h fumigated soil) minus (organic C extracted from a similar, non-fumigated soil)]. They proposed that biomass C can be estimated from the relationship: Biomass $C = 2.64\ E_c$.

The fumigation-extraction method (FE) does suffer from the disadvantage that comparatively small amounts of C have to be measured in 0.5 *M* K_2SO_4. Vance *et al.* (1987b) used a dichromate digestion method. However, the C can be more conveniently determined by an automated system using persulphate and UV oxidation, which gives essentially the same results but more rapidly and easily (Wu *et al.*, 1990).

Chloroform fumigation also increases the amount of total N extractable with 0.5 *M* K_2SO_4. Brookes *et al.* (1985) showed that this extra N also comes from the microbial biomass and proposed that biomass N could be estimated from the relationship: Biomass N = 2.22 E_N, where E_N is analogous to E_c.

About 16% of the *total* N released by $CHCl_3$ after 24 h and extracted by K_2SO_4 is in either ammonium-N or α-amino N. These forms react with ninhydrin giving a blue/purple colour and measurement of ninhydrin-N can be used to estimate the amount of biomass C (Amato and Ladd, 1988).

Following $CHCl_3$-fumigation there is also an increase in inorganic P (P_i) made extractable to 0.5 *M* $NaHCO_3$. Brookes *et al.* (1982) reported that biomass P could be estimated from measurement of this increase in P_i, with a correction made to account for incomplete extraction of P_i due to fixation on soil colloids, etc. and assuming that about 40% of the P in the soil microbial biomass is extracted by 0.5 *M* $NaHCO_3$ following $CHCl_3$-fumigation.

Sulphur is also released from the biomass during $CHCl_3$ fumigation and its measurement after extraction can also be used to estimate biomass S (Chapman, 1987; Saggar *et al.*, 1981; Wu *et al.*, 1993).

The FE method offers some considerable advantages over FI. Biomass measurements can be made across the whole pH range (Vance *et al.*, 1987a), in soils containing actively decomposing substrates, e.g. cereal straw, both in the laboratory (Ocio and Brookes, 1990a) and in the field (Ocio *et al.*, 1991a) and in freshly sampled soils, all conditions where FI is unreliable. Reliable biomass measurements by FE have also been reported in paddy (i.e. waterlogged) soils (Inubushi *et al.*, 1991). This is not discussed further here as this paper is restricted to aerobic soils.

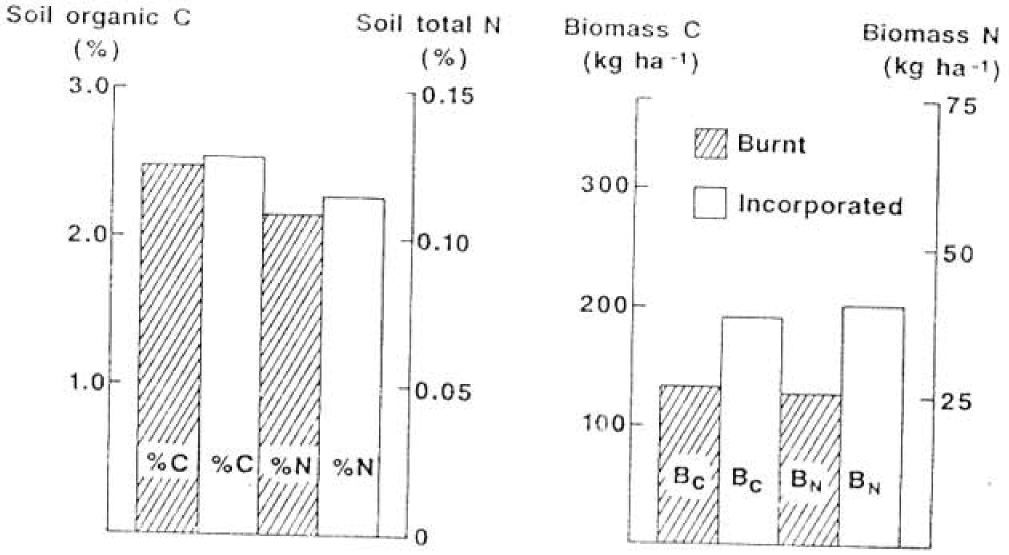
As with FI, the FE method is suitable for use with isotope tracer studies. FE has the big advantage that the labelled biomass that develops as substrates decompose can be measured immediately after substrate addition (Ocio *et al.*, 1991b; Wu *et al.*, 1993); this is impossible with FI.

Substrate-induced respiration method

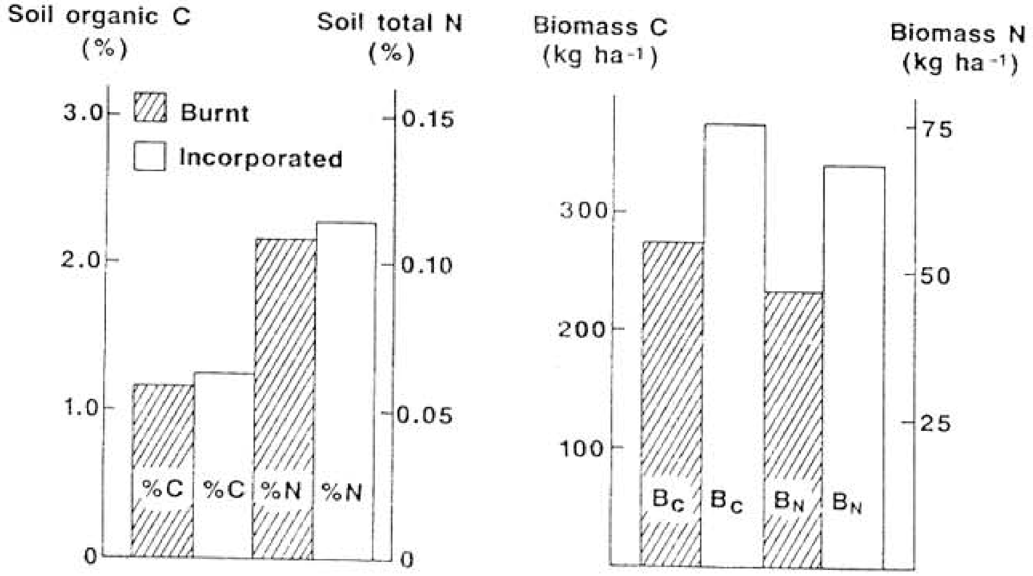
When glucose is added to soil there is a rapid increase in the respiration rate until, with increasing concentrations of added glucose, the respiration rate increases to a maximum, normally within 1-2 hours. Anderson and Domsch (1978) showed that following glucose addition, the rate of CO_2 evolution before cell division occurs was linearly related to the size of the initial biomass. They therefore proposed that measurement of the maximum respiration rate following glucose addition (SIR) provides a rapid estimate of the initial soil microbial biomass. Lin and Brookes (1992) reported successful measurements of biomass by SIR in soils which contained actively decomposing ryegrass and in recently fumigated soils. These are both conditions where microbial activity is much increased. This finding extends the use of SIR in soil microbial ecology considerably.

FIGURE 1

Percentage soil organic C and N and biomass C and N in Danish field soils where straw was burnt or incorporated for 18 years



STUDGAARD



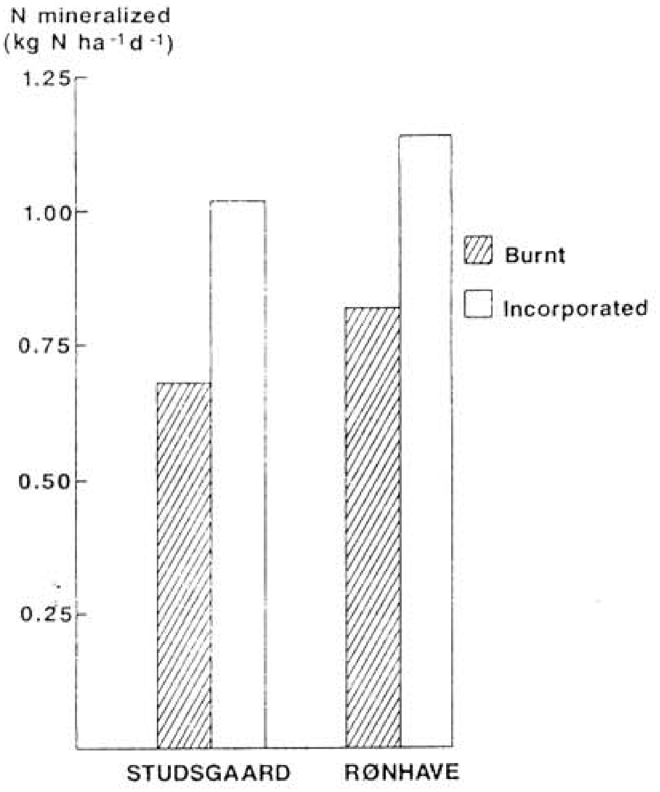
RØNHAVE

SOIL MICROBIAL BIOMASS AS AN EARLY WARNING OF CHANGING SOIL CONDITIONS

In most soils that are at or near steady state conditions (i.e. inputs are equal to outputs), biomass C comprises between about 0.5 to 4% of soil organic C and there is a reasonably close linear relationship between amounts of microbial biomass C and amounts of soil organic C in arable, grassland and woodland soils (e.g. Ayanaba *et al.*, 1976; Powlson and Jenkinson, 1976; Ross *et al.*, 1980; Jenkinson and Ladd, 1981; Sarathchandra *et al.*, 1984; Martens, 1985; Anderson and Domsch, 1989; Insam *et al.*, 1989). The soil microbial biomass increases or decreases in response to changes in soil management much more quickly than soil organic matter as a whole, where such changes can often take many years before being detectable by classical chemical analysis (Ayanaba *et al.*, 1976; Jenkinson and Ladd, 1981; Adams and Laughlin, 1981). Ayanaba *et al.* (1976) and Adams and Laughlin (1981) reported that changing from forest or grassland to arable management caused much greater decreases in biomass C than total soil organic C.

FIGURE 2

N mineralized during 60 days in the laboratory from Danish field soils where straw was burnt or incorporated for 18 years



Powlson *et al.* (1987) reported that 18 years of straw incorporation in two Danish field experiments, at Studsgaard and Rønhave, caused 40-50% increases in biomass C and N whereas total soil organic C and N only increased by 5%, a statistically insignificant increase (Figure 1). Both CO_2-C evolution and N mineralization over the 0-60 day period were significantly greater in the soils which had received straw than in control soils where the straw had been burnt. At Rønhave the increase in mineralized N was 38% and at Studsguaard 50% (Figure 2). This is direct evidence that an increased rate of return of crop residues to soil increases the labile pool of soil organic matter where mineralization-immobilization occurs to a much greater extent than the soil organic matter as a whole. Some of this N that is mineralized will be derived from mineral N immobilized during straw decomposition and some from N originally present in the straw (Powlson *et al.*, 1985; Ocio *et al.*, 1991b). The additional mineralization of N in straw-treated soils during the 60-day laboratory incubation was equivalent to more than 20 kg N/ha at both sites. Increases of this magnitude in the field, if they occur, are of agronomic significance and would permit fertilizer N applications to be decreased to some degree.

Similar results were also reported by Saffigna *et al.* (1989) for Australian soils. This, and much other similar work, supports the original idea of Powlson and Jenkinson (1976) that the biomass is a much more sensitive indicator of changing soil conditions than is total soil organic matter content so that the biomass can serve as an 'early warning' of such changes long before they may be detected in other ways. This is also illustrated here by other, more recent, work on the effects of heavy metals on microbial biomass and microbial activity.

There is now accumulating evidence that heavy metals at, or a little above, current permitted European Union limits decrease the proportion of biomass C in total soil organic matter. Thus, Brookes and McGrath (1984) reported that sandy-loam soils from the Woburn Market Garden Experiment which last received metal-contaminated sewage sludge more than 30 years ago (high-metal soils) contained up to 50% less microbial biomass than similar soils which received inorganic fertilizer or farmyard manure (low-metal soils) over this period. The high-metal soils now contain maximum amounts of Cu, Ni and Zn at around current EU limits and Cd at up to 3 times. Other work indicated that Cd at twice the current EU limit had no effects on biomass in a silty-loam soil (Chander and Brookes, 1991). The biomasses in the high-metal soils showed no correlation with total soil organic C, unlike the low-metal soils from the same experiment. Similarly, Chander and Brookes (1991) reported that biomass C as a percentage of total soil organic C was twice as large (1.5-2.0%) in non-sludged soils or soils which received non-contaminated sewage sludge than in soils which received sludges which were principally contaminated with Cu or Zn (0.7-1.0%) in two other UK field experiments.

So far, these types of data have only been obtained from carefully designed and controlled field experiments, with full plot replication. It is desirable that this work should be extended to non-experimental sites to determine the environmental impact of changing agricultural management or of pollution on soil organic matter and microbial dynamics. The collection of such data is always beset by the lack of a suitable uncontaminated control soil. The link between biomass C and total soil organic C, discussed above, may itself constitute an 'internal control' so that when soils deviate much from (biomass C)/(total soil organic C) ratios perceived as normal, for the particular management, soil type and climate, it may be a *preliminary indication* that some damage or change to the functioning of the soil ecosystem has occurred. Further, more detailed studies should then be undertaken.

BIOMASS AS A SINK OR SOURCE OF PLANT NUTRIENTS IN LOW-INPUT AGRICULTURE

Soil nutrient availability in low-input farming systems mainly depends upon the mineralization of crop residues, animal manures and of native soil organic matter. Many farmers outside of the developed world are too poor to afford much inorganic fertilizer so that there is usually a net removal of nutrients from the soil in the harvested crop. This will often be coupled with a decline in soil organic matter with time as the inputs of organic C in the crop residues or animal manures are seldom equal to the annual losses of organic C and N caused by microbial mineralization and soil erosion. Many farmers are therefore faced with declining soil fertility, with a resulting decrease in crop yield.

It is clear therefore that the correct management of crop residues and animal manures, while important enough in the generally more productive agriculture in temperate regions, is an essential part of the agricultural economics in developing countries, especially in tropical climates. If these organic inputs could be better managed this would have the direct result of improving crop yield, by increasing soil nutrient availability, decreasing erosion, improving soil structure and increasing soil water holding capacity.

The rate and efficiency of mineralization of the nutrients held in crop or animal residues, mediated by the soil microbial biomass, are key factors in determining the availability of nutrients to crops. It is also becoming widely accepted that the fertility of both natural and agricultural tropical ecosystems depends upon the nutrients being very efficiently cycled within the organic pools of plants, microbes and soil organic matter. In this way, losses of nutrients from the ecosystem are minimized. For example, many tropical soils have exceedingly high P-fixation capacities so that P is rapidly and irreversibly fixed and becomes unavailable to plants. However, if cycled within the organic pools, as described above, such losses from plant-available forms can be minimized (e.g. Sanchez, 1976).

There is evidence that the microbial biomass constitutes an organic matter pool of potentially available, but protected, plant nutrients in tropical ecosystems. Thus, Singh *et al.* (1989) reported that the microbial biomass is an important source of plant-available N in tropical soils. The biomass declined in size as N mineralization increased following the rewetting of such soils, precisely during the period when plant growth was most rapid. They therefore considered that the microbial biomass acted both as a sink and a source of nutrients in these nutrient-poor systems. It thus functioned by accumulating and conserving nutrients in a biologically active form during the dry period (large biomass - low turnover) when the ability of plants to extract nutrients from soil was low. It then released nutrients rapidly once the soils became wet, so stimulating plant productivity (small biomass - fast turnover). Similarly, Lethbridge and Davidson (1983) reported that in a soil of low N content, the N contained in added micro-organisms was as effective in supplying N to plants as an equivalent amount of nitrate-N.

Until recently it was not possible to quantify the sizes of the microbial pools of plant nutrients, e.g. N, P, S, as they formed during the early decomposition of crop or animal residues. Neither was it possible to monitor the fluxes of nutrients under these conditions as they passed through the biomass, and thence into mineralizable forms. Recent breakthroughs in methodology now make this possible (e.g. Ocio *et al.*, 1991b; Wu *et al.*, 1992), using both unlabelled and isotopically labelled plant material and other substrates.

There is evidence that the biomass takes nutrients preferentially from plant residues rather than the soil inorganic nutrient pool (Ocio *et al.*, 1991b). Thus the composition and characteristics of plant residues will have a major influence on the availability of nutrients to crops and their subsequent cycling. Factors such as C/N ratio, percentage of readily decomposable and resistant plant tissue or lignin content will have an important effect on the uptake and subsequent mineralization of crop-derived plant nutrients (Anderson and Ingram, 1992).

Techniques for monitoring *in situ* mineralization and the fractionation of soil organic matter into meaningful fractions in relation to its significance in plant nutrient cycling have also been evaluated (Anderson and Ingram, 1992).

There is evidence that soil residue management in tropical agriculture becomes increasingly important when inorganic fertilizer is also supplied. One Ethiopian experiment in particular deserves mention (IAR, 1987a, b). Maize residues were either incorporated, burnt or removed in field plots at Bako, Wallenge, Ethiopia. Each treatment also received N fertilizer at up to 75 kg N/ha. While N fertilizer increased yield in all treatments, in 1984-5 the yield was 45% higher, and in 1985-6 80% higher at the highest fertilizer rate, where residues were incorporated compared to yields when the high rates of N were supplied but the residues were burnt or removed. There was also evidence for a cumulative beneficial effect of the residues at the highest fertilizer rate. Reasons for this increased efficiency in N fertilizer use at higher rates of residue incorporation require investigation. They may include increased water retention and improved soil structure due to the higher soil organic matter content. There may also be increased assimilation of N by the microbial biomass at the higher fertilizer rates in the presence of residues. This N may then become available again through the process of biomass turnover. The concept of biomass turnover and its measurement are discussed below.

TURNOVER OF THE SOIL MICROBIAL BIOMASS

The methods available to measure the 'standing crop' of soil microbial biomass, while having their limitations, have given estimates of pool sizes of C, N and P in the biomass which generally fit with perceived reality. They certainly allow work towards an understanding of soil nutrient dynamics which would be impossible if micro-organisms could only be studied as single species or families in soil (Powlson, 1993). Linked with this is the concept of biomass turnover, leading to estimates of the flux of nutrients through the biomass. It is really by these processes that soil nutrients are made available to plants by microbial activity. Estimates of biomass turnover times, defined for example for P as: [(Biomass P content, kg P/ha)/(Annual input of P into the biomass, kg P/ha/yr)] and flux of P through the biomass, as [(Biomass P content, kg P/ha)/(Biomass P turnover time, yr)] can provide estimates of soil nutrient fluxes in agricultural or natural ecosystems.

Jenkinson and Rayner (1977) proposed a turnover time of 2.5 yr for biomass C measured in the Broadbalk Continuous Wheat Experiment under UK field conditions and a turnover time for N of 1.52 years was proposed for the biomass in soils of the same experiment, again measured under field conditions (Jenkinson and Parry, 1989). The measurements of turnover of biomass C were based upon measurements of inputs and declines of ^{14}C in soil as a result of the atomic bomb tests in the 1960s. At this time a pulse of ^{14}C-labelled C entered the global soil organic matter pool giving, hopefully, a unique chance to undertake these measurements. The turnover time for biomass N of 1.52 years (Jenkinson and Parry, 1989), also obtained under field conditions, was done by adding ^{15}N-labelled inorganic N fertilizer to the soil. A part of this (3.4%) entered the biomass immediately after ^{15}N addition and the rate of decline of ^{15}N in the biomass was measured over the following 4 years. Appropriate mathematical models were fitted to the data in both cases to obtain these values. Full experimental and theoretical details of these and other field measurements of biomass turnover are given by, for example, Jenkinson and Rayner (1977), Chaussod *et al.* (1988) and Jenkinson and Parry (1989). While it is clear that these and similar measurements are best made under field conditions, the cost, expertise and time required (often several years) often make this an impossibility. The need to use radioactive isotopes in many cases causes further restrictions, although the increasing use of the non-radioactive isotope ^{13}C may accelerate research into C dynamics under field conditions. Certainly, any proposal to measure biomass P dynamics, using ^{32}P or ^{33}P under field conditions would now face a plethora of restrictions and regulations which would daunt all but the strongest hearted.

However, there is some evidence that laboratory measurements of biomass turnover, while having limitations, may be useful measurements, provided extrapolation to field conditions is done with caution. The basis of the procedure is that, following the addition of a substrate to soil, the turnover rate of biomass that develops on the substrate is initially much faster than that of the biomass as a whole (Wu, 1991). After a period (usually about 10 days) the turnover rate of the newly synthesized biomass approximates to that of the biomass as a whole. Thus, by measuring the rate of disappearance of the labelled biomass, the turnover time of the whole biomass may be determined under laboratory conditions.

It seems likely that changes in total soil organic matter should be related at an early stage to changes in biomass turnover. This is because soil organic matter itself is mainly composed of microbial metabolites with only small amounts of very resistant undecomposed plant and animal remains. Thus the balance between rates of microbial processes leading to organic matter accumulation and those involved in organic matter degradation largely determines the amount of organic matter in a soil within the constraints of soil type and climate.

The difference in biomass C turnover times measured by the method of Wu (1991), in a sandy (9% clay) soil and a clay (40% clay) soil from UK sites are shown in Table 1. Clay soils contain more soil organic matter and have a larger biomass (with a slower rate of respiration) than sandy soils under the same management. Thus clays can be considered to stabilize both microbial biomass and soil organic matter, although the mechanisms are not fully understood (e.g. Jenkinson and Ladd, 1981). The biomass in the sandy soil had a much shorter turnover time (125 days) than that in the clay soil (383 days). Thus, the rate of transformation of fresh substrates such as plant residues and soil organic matter by the biomass in the sandy soil was several times faster than in the clay soil, presumably leading to the smaller amounts of total soil organic matter in the sandy soil (Table 1). Although the estimated total annual C inputs to the clay soil (1.9 t C/ha) were greater than to the sandy soil (1.1 t C/ha), this difference (Wu, 1991) was far too small to account for the difference in total soil organic matter (1.1% C for the sandy soil and 3.4% C for the clay soil).

The measurements of biomass turnover times were done at 25°C. This was partly to be able to make the measurements within the reasonable time period of 100 days. At lower soil temperatures (as in the field in temperate climates) the turnover time would obviously be longer. If it is assumed that the Q_{10} rule applies (i.e. there is a doubling in rate for a 10°C rise in temperature), this would give biomass turnover times at 10°C of around 0.8 years for the sandy soil and 2.6 yr for the clay soil. The validity of this extrapolation needs to be tested before it can be used with confidence. However, these turnover times are of the order of other turnover times estimated for the biomass under field conditions (e.g. Jenkinson and Ladd, 1981). The concept of biomass turnover time may well be a useful approach in attempting to explain, or predict, the accumulation or decline of soil organic matter resulting from changes in residue management or land use.

TABLE 1

Biomass C turnover time in a sandy and clay soil from the UK both given NPK fertilizer (Wu, 1991)

Soil	Texture	Soil organic C (%)	Estimated total annual C input (t C/ha per year)	Biomass C soil (μg C/g soil)	Biomass C turnover time (days)[a]
Woburn	Sandy (9% clay)	1.10	1.1	125	125 ± 5
Northfield	Clay (40% clay)	3.39	1.9	788	383 ± 35

a = at 25°C and 40% WHC.

Recently a procedure has been developed to measure the turnover times of biomass P and biomass C simultaneously in the same soil, under the same conditions in the laboratory (with Dr K. Kuono, University of Hiroshima, Japan). The method involves addition of ^{14}C-labelled glucose to soil containing $KH_2{}^{32}PO_4$ which has been allowed to equilibrate for 5 days with unlabelled native soil inorganic P prior to glucose addition. The apparent turnover times of biomass C and P were estimated by applying first-order kinetics rate equations to the declines in ^{32}P- and ^{14}C-labelled biomasses at 25°C and 40% water holding capacity (WHC). Assuming that turnover times of biomass under field conditions in a temperate climate are about 4 times slower than under the above laboratory conditions (Chaussod *et al.*, 1988), this gives mean field turnover rates for both native and recently synthesized biomass P of about 0.4 yr and for biomass C of about 1.0 yr, measured in a Rothamsted soil of about 23% clay. Using these values, the mean biomass P flux through 6 UK arable soils was about 40 kg P/ha/yr and about 140 kg P/ha/yr for UK grasslands.

The faster turnover time for P than C seems reasonable as the P will be almost entirely within the cell membranes and cytoplasm of the micro-organisms, while the C will also be an important constituent of the cell wall. Microbial cell walls are known to be much more stable in soil than the intracellular components (e.g. Jenkinson and Ladd, 1981). The results strongly indicate that the microbial biomass is far from being a static component of the total soil organic matter pool and that the flux of nutrients through it can be surprisingly large. Phosphorus coming from biomass turnover will help replenish soil inorganic P pools.

It must be emphasized that ideas about the measurement of biomass turnover times and the quantification of fluxes of nutrients through the biomass are still evolving. In particular the fluxes of P through the biomass as measured by ^{32}P seem large, although there are few, if any, similar measurements to serve as comparisons. Calculated fluxes of P through the biomass, usually based on 'standing crop' measurements of biomass P and an assumed turnover time of 1.5-2.5 yr (e.g. Brookes *et al.*, 1984; Srivastava and Singh, 1991) are generally around 10 kg P/ha/yr for temperate arable soils and 25 kg P/ha/yr for grassland or forest. More work is needed to evaluate these discrepancies. Also the proportions of nutrients that are made available to plants during biomass turnover are not known. Some will be sorbed by the soil, some will be utilized directly by the soil microbial biomass, and some may be lost by leaching or erosion.

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Effect of supply of organic inputs on soil fertility on western semi-arid African savannahs

The soils of the Soudano-Sahelian area in Africa are mostly sandy, with low organic matter content (Alfisols). During the last decades, increasing population pressure has led to the modification of the cropping systems from shifting cultivation to permanent cropping in many areas. This evolution caused the degradation of the cultivated land, in particular through a sharp decrease of the organic matter content of the topsoils. Thus, the cropping systems should maintain or restore the required level of soil organic matter for achieving an intensified but also a sustainable agriculture.

While the beneficial role of the soil organic matter (SOM) on soil properties is widely recognized, the impact of the supply of organic materials to the topsoil for maintaining the productivity of the land is controversial. According to some authors, the supply of mineral fertilizers, if economically profitable and associated with sound cultivation practices, is more effective than the supply of organic materials for soil fertility maintenance (Sánchez, 1976; Dudal and Deckers, 1993). According to other authors, the soil fertility can only be maintained or restored through the supply of organic materials like manures and composts (Pieri, 1989; Wey *et al.*, 1987).

This paper discusses the role of the supply of organic materials in soil fertility maintenance and restoration. In fact, in many publications, the supply of organic materials to the soil and the soil organic matter are confounded in the general concept of 'organic matter'. This generic term creates confusion when evaluating the role of the two materials for upgrading the soil fertility (Sánchez *et al.*, 1989). The composition and function of SOM in tropical soils are reviewed and the effects of cultivation on the mineralization of SOM are analysed. The impacts of the supply of soil organic materials to the topsoil are described and the potentials for the use of organic materials in cropping systems in West African dry savannahs are evaluated.

MAIN CHARACTERISTICS AND FUNCTIONS OF THE SOIL ORGANIC MATTER

Content and composition of SOM in tropical soils

The composition of the SOM in tropical soils is not very different from what has been identified in temperate soils (Sanchez, 1976). The SOM content presents a wide range of values in tropical areas. Climatic factors (temperature and rainfall) influence SOM content

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PAPER 2.3

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(Jenny *et al.*, 1948) and soil factors are influential as well and sometimes predominant (Feller, 1993). Thus, the low clay content of the Alfisols in Soudano-Sahelian West African areas conditions the low soil organic matter content of the soils in this region (Pieri, 1989).

The components of SOM in tropical soils are comparable to those present in temperate soils. Laboratories apply similar analytical methods for their characterization (Theng *et al.*, 1989). Physically and chemically the following components can be distinguished:

- plant and animal residues in various stages of decay (macro OM or light fraction);
- easily identifiable non-humic products (carbohydrates, lipids, organic acids, protein);
- humic components.

The latter components are complex and heterogeneous. No defined chemical structure can be recognized in those materials. Classically, they are subdivided into three fractions according to their solubility in reference solutions with contrasted pH. They range from less stable forms to alleged more stable forms: fulvic acids, humic acids and humin. Recently, this distinction has been found to be rather artificial as far as no clear limits can be established between these three fractions. Moreover, the stability of a fraction of soil organic matter may be related to the absorption of this produce on mineral particles or to the sheltering of this fraction by films of mineral compounds (Duxbury *et al.*, 1989).

SOM can be physically divided into granulometric fractions. The reactivity and chemical composition of SOM associated with the class size of particles have proved to vary. Thus the humification of the organic compounds increases when the size of the particles is decreasing (Feller, 1983). Therefore, SOM should be regarded as a collection of organic pools presenting various life period times, in particular when modelling SOM evolution is attempted. For example, Parton *et al.* (1987) distinguish an active pool, a modification with a low pool and a passive pool. However, presently no methods are available for separating those pools and it could be that those pools are not 'discrete units' (Sánchez *et al.*, 1989).

In the Alfisols of the Soudano-Sahelian zone, the so-called light fraction of SOM, composed of plant residues in various stages of humification, may represent up to 50% of the total SOM (Feller *et al.*, 1983). The fraction of the organic matter that is linked to the clay depends merely on the clay content of the soil. Sandy soils are reported by many authors to have a typically high degree of humification of the organic matter linked to the clay, with the humin fraction representing 75 to 90%. Up to 50% of the humin is nevertheless found in the light fraction (Feller *et al.*, 1983).

Functions of soil organic matter in soils

The functions of the SOM vis-à-vis soil properties are diverse. One may distinguish 3 categories of functions:

- source and sink of plant nutrients;
- support for soil fauna and flora;
- active component of soil physical properties.

Soil organic matter as a source and a sink of plant nutrients

The decay of the different pools of organic matter in soils releases plant nutrients (N, S, P, B) which were included in molecules and cations absorbed, linked or complexed (Na, K, Ca, Mg, Fe, Al, Cu, Zn). The pattern of plant nutrient release depends on the respective proportion, on the nutrient content and on the turnover time of each pool. Therefore, the evaluation of the rate of the nutrient release from soil organic matter over a certain period of time is a complex issue. Additionally, the supply of nutrients from SOM is also depending on the demand from the crop and on the agronomic conditions created by soil management and cultivation practices (drainage, tillage, liming, supply of plant nutrients).

In tropical soils, the SOM supplies most of the nitrogen and sulphur and 50% of the phosphorus taken up by unfertilized crops (Sánchez 1976). According to several detailed evaluations in semi-intensified cropping systems, the SOM still supplies up to 80% of the nitrogen taken up by crops (Chabalier, 1976; Ganry, 1990). Thus, the slow release of N from soil organic matter is an important limiting factor in cropping systems. In the semi-arid tropics, most of the labile fractions of the soil organic matter are mineralized through the first rains of the cropping season (flush) when the rooting systems of the crops are not able to take up this nitrogen, which results in important losses through leaching.

The soil organic matter has a very high cation exchange capacity per unit of weight as compared to the clay, especially if the clay is composed of kaolinite or iron and aluminium oxides and silicates. Thus, especially in sandy soil, the soil organic matter provides most of the soil cation exchange capacity.

Soil organic matter, support for soil fauna and flora

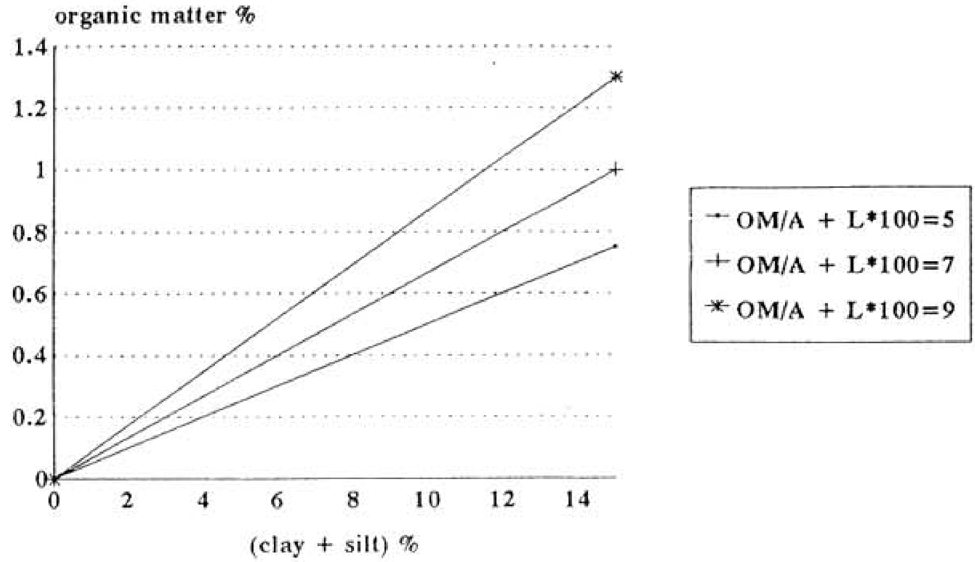
The SOM provides energy, carbohydrates and nitrogen to a large number of soil micro-organisms and soil fauna species. Interactions between the soil organic matter content, the activities of the micro-organisms, soil fauna species and the biomass of the natural vegetation and crop species are very important. However, the critical value of the soil organic matter below which the soil biological activity is significantly affected is insufficiently documented. In sandy soils, in the semi-arid tropics of West Africa, the threshold values could be in the range of 0.2 and 0.6% of soil organic matter in the topsoil (Pieri, 1989).

The effects of some particular compounds of the soil organic matter on crop physiology have been reported. Thus the organic acids of low molecular weight could limit root formation and development and cellular permeability. Humic acids could, thanks to their phenolic and quinic functions, be absorbed by the roots. The documentation about the possible action of organic matter components on plant growth is scarce and controversial.

Soil organic matter, active component of soil physical properties

The stability of the soil structure depends on the soil organic matter content in tropical sandy soils. It has been stated by many authors that the pool of organic matter content, with a slow rate of decay, plays a major role in stabilizing the micro-aggregates in soils, while the passive pool of soil organic matter components is mainly binding the soil particles together (Sanchez *et al.*, 1989). Recently a detailed analysis proved that the polysaccharides and the humic substances both contribute actively to the stabilization of the aggregates in soils through

FIGURE 1
Critical levels of organic matter for the maintenance of physical soil properties



complex associations of clay organic matter and mineral components (iron and aluminium oxides, silica, cations) (Dutartre *et al.*, 1993)

In very sandy soils (on sand dunes for example), the classical evaluation of the soil structural stability through the technique elaborated by Henin is quite difficult because the stabilized aggregates represent a very limited fraction of the total soil. The soil presents an organization and physical properties which clearly depend on the soil organic matter content and on the content of the soil of thin particles. Thus Pieri (1989) has proposed a stability index for semi-arid tropical sandy soils (St% = 100 x OM%/clay + silt %). If this ratio is lower than 0.9 the soils are considered to be very sensitive to the degradation of their physical properties (Figure 1).

The soil organic matter content affects the hydrodynamic properties of the topsoil, either indirectly through the effect on soil structure, or directly through the high water holding capacity of the humic substances which can, theoretically, retain fifteen times their own weight of water. In sandy soils, Sánchez (1976) reports that the water holding capacity of the soil decreases between 57 and 37% of the initial value when SOM decreases from 5 to 3%. When dried out, humic substances can be water repellent, which could explain a part of the contribution of the soil organic matter to the resistance of the aggregates in soils. In sandy soils very rich in organic matter and severely dried in semi-arid tropics, the repellency to water of the soil may affect the way the water infiltrates in the soil, thereby inducing preferential flow paths.

Evolution of SOM content under continuing cropping systems

Through continuing cropping systems initiated after a long term fallow, the organic matter content of the soil firstly decreases quite rapidly and then slowly stabilizes at a lower level than the level observed with the fallow. The rate of decrease of the soil organic matter content and the speed of the modification towards a new equilibrium depends on the soil type, the level of the fertility of the soil and on the management of the cropping system. Under intensive cropping, the total decrease of the soil organic matter content, from a long fallow system to the new equilibrium can reach 50% in sandy soils and in semi-arid climates of Western Africa (Pieri, 1989). Feller *et al.* (1991) observed that in controlled conditions the equilibrium from fallows to intensively cropped soils was reached in 3 years in very sandy soils and in 10 years in more clayey soils under the same ecological conditions.

In West African dry savannahs (Senegal and Burkina Faso), the annual decrease rate of the soil organic matter (K coefficient) under traditional farming was evaluated by CIRAD agronomists from long-term experiments (Pieri, 1989). Values of K were found to be close to 4% in very sandy soils and about 2% in loamy sands. The mineralization rate of the soil organic matter is increased because of the increased soil temperature, soil aeration, the increased frequency of desiccation and wetting and the acidification of the soil by cultivation. Cropping practices may markedly affect K values. For example, in a very sandy soil from Bambey (Senegal) regular ploughing of the topsoil increased the K value from 5% to 7% compared to no tillage.

In fact the fractions with a rapid turnover are much more affected by this decrease of soil organic matter than the fractions with a very low turnover. Thus the supply of nitrogen, sulphur and phosphorus by a soil is sustainable if the decay of the soil organic matter from which those nutrients are provided is compensated by the equivalent renewal of organic materials in the considered fractions.

ORGANIC INPUTS

Different effects of organic inputs

The major difficulty in assessing organic input efficiency, as compared to inorganic fertilizers and amendments, lies in the fact that organic inputs have several distinct effects.

One of the functions of organic inputs is to supply nutrients to crops. In fact, in numerous studies, organic input efficiency was essentially explained by its nutrient composition (Sánchez, 1976). High content of Ca and Mg may also, in some cases, explain the efficiency of organic inputs, because such elements are often neglected in inorganic fertilization. Considering organic inputs only in terms of their mineral composition infers that they are rapidly mineralized. Such an assumption may be realistic under the pedo-climatic condition of the zone. However, as mineralization occurs at the beginning of the growing period, when crop needs are low, some elements (especially nitrogen) may be lost by leaching or volatilization, resulting in a reduction of the nutrient supply from organic inputs.

Another function of organic inputs is to supply an energetic substrate to soil micro-organisms. This function may be of major importance in very degraded soils, where energetic substrate may become a limiting factor to biological activity. The enhancement of biological activity, induced by organic inputs, leads to an increase of the microbial pool of nutrients, the importance of which for the nutrient release pattern of soil is increasingly being recognized (Sanchez *et al.*, 1989). Organic inputs may also contain organic compounds likely to influence root development and growth.

Organic inputs may have an immediate effect on soil physical properties through the action of intermediate products of their decomposition (polysaccharides and polyuronides).

All the effects mentioned above are linked to the decomposition of organic matter, and therefore are not likely to be durable. Durable effects can be expected only when organic inputs lead to the formation of new soil organic matter. In this case, both nutrient release patterns and biological or physical characteristics of the soil can be modified. That organic inputs lead to SOM formation is sometimes considered so evident that organic inputs and SOM are often not distinguished by agronomists. However, processes by which organic inputs participate in the formation of new SOM are poorly understood. In fact, very contradictory data appear in the literature, showing either SOM increase or even decrease after the application of organic inputs. About the consequences, for example, Lal *et al.* (1980) observe a significant improvement of soil physical properties induced by organic inputs, while Cissé (1986) could not detect any physical improvement of soil after years of regular organic inputs. These apparent contradictions led to emphasize that no general statements can be made about organic input effects, because of the high variety of input quality, and because different placement and environmental conditions may induce opposite effects.

Conditions of SOM formation

The factors that influence SOM formation from organic inputs are discussed below, including the nature of SOM pools concerned, bearing in mind that knowledge in this area is generally lacking.

Effect of organic input quality

Organic input quality was originally defined by the C/N ratio. However, other properties, related to the type of C compounds, influence the rate of decomposition. Some of these compounds are easily fermentable (cell sap, cellulose, etc.) while others are much more resistant (cell walls, lignin, etc.). Ratios such as lignin/N or fibre/cell content (NDF/CC) where found to be better indicators than C/N. For example Gueye and Ganry (1978) studied the effect of high C/N inputs on SOM formation. They showed that sorghum straws (low NDF/CC) caused mineralization of the organo-mineral fraction of SOM, while composted groundnut shells (high NDF/CC) significantly increased the soil organo-mineral fraction. Hardly bio-degradable material, such as non-composted groundnut shells, increased total carbon content of soil without affecting organo-mineral fraction.

To the present knowledge, it can be summarized that material containing humic or prehumic compounds (composted) can contribute to the formation of stable SOM, while easily degradable materials, with high C/N, do not contribute to SOM formation and can even lead to a negative SOM balance.

Form of organic inputs

Four principal forms of organic inputs can be distinguished: (i) green manures, (ii) cereal straws, (iii) animal manure and composts, and (iv) roots.

The incorporation of green manures improves structural stability and biological activity of the soil, but this effect is not durable. The positive effect of repeated inputs on crop production has been demonstrated on sandy soils at Bambey, Senegal. However, incorporation can be followed by immobilization of mineral nutrients such as N, S and even K. In order to avoid deficiencies, these elements should be supplied by mineral fertilization. In the long term, green manures do not contribute to SOM formation.

Cereal straws inputs can lead to negative effects on crop production in the short term, because of important N immobilization and the possible release of phytotoxic compounds. In the long term, they can contribute to the formation of SOM, depending on temperature, soil moisture and biological activity.

Animal manures and composts appear as the better way of improving productivity either in the short term (by supplying mineralizable nutrients) and the long term (by formation and maintenance of SOM), when applied in sufficient quantity (about 2 tons of dry matter/ha/yr).

The root system of the preceding crop constitutes an organic input. Living roots divide the soil and stabilize aggregates both physically (role of root hairs) or by organic exudates (mucilages) acting as cements. Dead roots can constitute an important and well scattered input of fresh organic matter in the soil. However, despite the probable importance of organic input by roots, especially in low input farming, virtually nothing is known about its fate in the soil, due mainly to difficulties in measurement.

Effect of organic input placement

Although much must be learned on this topic, placement probably determines to a large extent the fate of organic inputs in soil. Feller *et al.* (1987) showed that restitutions of millet straws enriched the organo-mineral fraction of SOM when applied as mulch, whereas they enriched the 'light fraction' when incorporated in the soil. Placement acts by affecting both the physical and biological properties of the soil.

Present perspectives of organic input management in West African savannahs

Fixation and intensification of agriculture in tropical savannahs require the improvement of soil fertility management. Restitutions of animal and vegetal wastes are in most cases the sole inputs available to farmers. Assuming an annual mineralization rate of SOM of about 2%, evaluated global needs are about 600 kg/ha/year of humified organic matter (or 2 tons of dry matter of compost). As current cultural systems (eventually including groundnuts or cotton) are based on cereals (sorghum, millet, maize, rice), it appears that only cereal straws are likely to provide sufficient inputs.

Management of residual straws

Cereal straws generally require sound modifications before being restituted, because of their generally high C/N ratio and of the phytodepressive effect of some compounds (phenolic acids) they may contain.

Maize straws represent about 2-3 tons of dry matter/ha. Because of their relatively low C/N ratio, their systematic incorporation should induce a significant increase in SOM, likely to improve soil physical properties. However, phytodepressive effects have sometimes been reported (Guiraud *et al.*, 1980). In fact, maize straws are rarely restituted directly by farmers but rather used as fodder. Their transformation in cowsheds produces a manure of a satisfying degree of humification.

Sorghum or millet straws represent about 4-6 tons of dry matter/ha. Their high C/N, their consistency and the presence of toxic phenolic compounds imply that they need to be modified prior to their restitution to the soil. Therefore, animals play an essential role in the valorization of sorghum straw.

Rice straw represents about 3-4 tons of dry matter/ha. Their direct incorporation is possible only at the end of the humid season, when soil moisture allows for a rapid transformation. However, their transformation by animals is always preferable.

In conclusion, cereal straw valorization as organic inputs to the field is linked to a better integration of animal breeding with agriculture.

CONCLUSION

Soil organic matter improves the quality of soil, partly by improving its physical properties. SOM content should thus be maintained at an acceptable level, above critical values corresponding to structural stability or biological activity. Cultivation reduces the SOM content. Inorganic fertilizers may in some cases reduce these losses, or even induce an increase in SOM content, mostly by increasing root restitutions. However, in most cases, they lead to an increase of the soil biological imbalance. In degraded land, inorganic fertilizers alone are not sufficient to improve crop yields and to restore soil fertility.

Organic inputs are often recognized to increase SOM content. However, the effect of organic inputs on the formation of the different pools of SOM is poorly understood. This partly results from the fact that the quality of organic materials is highly variable and that their input can result in opposite effects. Fresh organic matter can immediately improve soil stability through the action of polysaccharides or polyuronides. However, this effect is not likely to be durable. In several cases, it has been shown that fresh organic matter application leads to a decrease in SOM content. Durable effects can be expected if prehumified substances are incorporated into the soil, because of an increase of the organo-mineral fraction of SOM. The effect of placement (mulching) should be more intensively studied.

In the Soudano-Sahelian zone, cereal straws constitute the most important source of organic matter. Their ability to constitute organic inputs, likely to improve the SOM content, is related to their quality improvement. Technical ways of improving their efficiency (transformation through animals, compostage, incorporation, etc.) are often not available to local farmers. This is why organic residues are rarely restituted to fields in their original form.

A better valorization of available organic matter necessitates (i) a better understanding of the fate of organic inputs in the soil, and (ii) the elaboration and proposal of cultural systems adapted to the socio-economic conditions of the zone.

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Management techniques of organic materials in sustainable agriculture

It is generally claimed by scientific and extension advisers that the utilization of organic fertilizers of both animal and plant origin is of particular interest to sustainable agriculture. Researchers at an international level attribute considerable importance to the use of organic wastes, such as sludges and composts of solid urban wastes. However, beyond the possible impact of pollution due to the presence of heavy metals and undesirable substances, it is also indispensable that the application of these materials be agriculturally effective, a consideration which is often neglected. It is important that all the organic fertilizers used make a positive contribution to the organic matter balance. From an agronomic point of view, the most important parameters to evaluate the quality of biomass are the organic matter content and its characterization.

In addition to agronomic considerations, the utilization of organic wastes by farmers must also be encouraged, on account of its usefulness for the entire human society. Indeed the natural fate of wastes is to be recycled and to return nutrients to the soil. Sustainable agriculture, therefore, should be able to meet the needs of a sustainable society.

The techniques of managing organic materials are important to improve their quality and to make them suitable for application to the soil. After giving a short description of organic wastes available, this paper discusses the methods currently used for their stabilization. Special emphasis is given to the methods which can be employed to establish quality criteria of soil organic matter and to follow both the stabilization processes of organic amendments and the turnover rate of organic materials in soil. A final section is devoted to the management of organic matter in contrasted ecological conditions.

ORGANIC WASTES

Organic fertilizers are obtained from organic wastes that may be divided into two different groups. The first group is made up of animal and plant by-products that are rich in organic N and C, such as leather meal, ground feathers, horn and hooves, waste wool, oilseed cakes, and so on. All these materials contain more than 5% (sometimes 10-15%) organic N, and 30-50% organic C. The second group is composed of materials comparatively poor in organic N, such as animal dung or compost from urban refuse. Their organic N content is generally about 1%, while the organic C content is variable. Such materials are often called organic amendments.

PAPER 2.4

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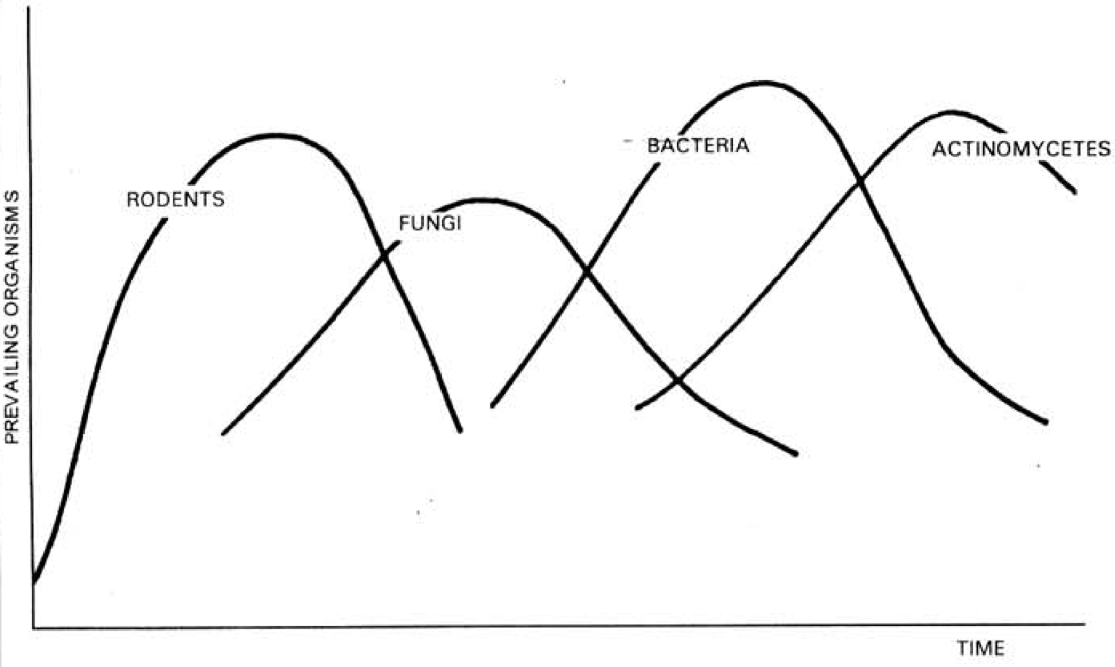
FIGURE 1

Example of a succession of organisms during transformation of an organic waste. The scales are arbitrary (after Sequi, 1992)



The organic matter of wastes is generally unsuitable for application to the soil. This unfitness is due to poor physical conditions: either the waste may be deliquescent or sticky, so that it can hardly be shovelled and incorporated to the soil, or it can be excessively hard which leads to difficult degradation by soil micro-organisms and mechanical hindrance to tillage and growth of plant roots. Furthermore, wastes are rich in easily decomposable organic matter, which cannot be applied to the soil as such because it may contain phytotoxic substances which undergo rapid transformation and give rise to an anaerobic environment which is toxic to plant roots and causes undesired reactions in the soil.

Organic wastes with high C and N contents can be applied to the soil in order to supply (i) nitrogen, which will be released slowly to plant roots, and (ii) carbon, which will be used by soil organisms as both a nutrient and energy source. After eventual hydrolysis, at high temperatures and pressures, materials rich in proteins are very resistant to enzymatic attack. Through concentration and desiccation of materials rich in water, organic wastes may be transformed to high quality fertilizers. Typical organic amendments, on the contrary, cannot be applied to the soil without first having been subjected for a period of time to organic matter stabilization often called 'maturation'. The use of raw organic amendments, in fact, may be inappropriate for several reasons as previously stated. During maturation of organic amendments, the total organic carbon content generally decreases, while the proportion of humified against non-humified carbon increases.

Organic amendments represent by far the largest amount of wastes, and their management is especially critical in sustainable agriculture. The main processes of stabilization or maturation of the organic matter consist ofhe proper use of aerobic or anaerobic treatments and will be briefly reviewed in the next section. Two major tasks are imperative for evaluating the quality and optimal use of organic wastes in agriculture. The first is to assess the actual stage of the 'maturation' of organic amendments quantitatively, so as to improve the transformation processes and to be able to utilize the amendments at the proper time. The second is to distinguish qualitatively different sources of organic matter, so that unknown materials may be easily recognized. These assessments can be made by following the increase of humified components during the aerobic or anaerobic treatment of organic wastes and by extracting and characterizing the organic components of the organic biomass through appropriate, e.g. electrophoretic, analytical procedures. The combined use of these techniques allows to follow the course of transformation of an organic fertilizer even after it has been added to the soil.

STABILIZATION PROCESSES OF ORGANIC WASTES

Organic wastes are the subject of a natural recycling system operated by waste treatment organisms. Their sole purpose is to degrade complex materials into simple molecules that will become the building blocks for new biosynthetic pathways and life cycles.

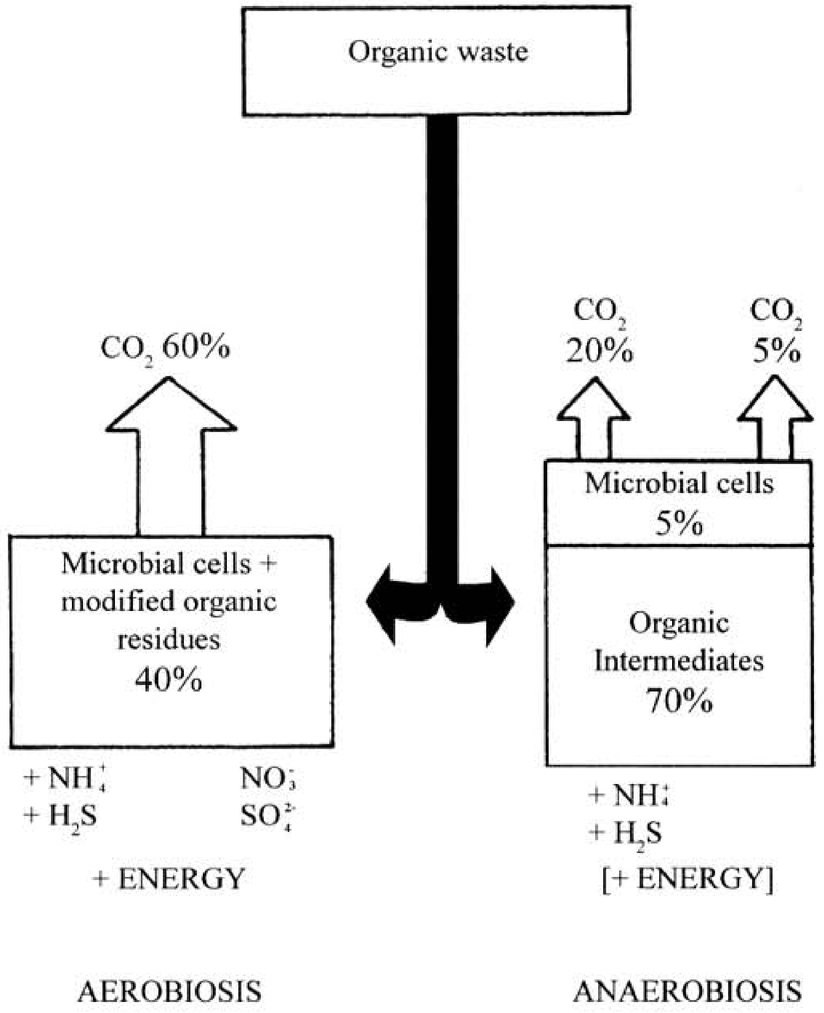
However, this general assumption applies neither to the whole technical process of transformation of wastes nor to the fate of wastes in soil. In fact, they are largely processes of stabilization and not of simple biodegradation.

Under natural conditions, many organic residues are decomposed by the successive actions of different animal and microbial populations, including some forms of mesofauna and micro-organisms (Figure 1). Hence, if rodents are mainly responsible for a reduction in size of coarse residues to little bits which facilitates the action of following populations, actinomycetes are generally the last term of the succession. They stabilize the organic remains also by producing antibiotics. As a matter of fact, no living population consumes its available organic food completely. The materials that are stored may be considered a reserve of energy, and become humified, i.e. stabilized,for some time.

Stabilization processes under natural conditions can differ greatly in contrasted ecological conditions. For instance, in arid or semi-arid areas the action of mesofauna may largely prevail so that non-humified or poorly humified organic debris may accumulate in soil. In agricultural soils under temperate climates mesofauna may practically disappear because of soil disturbance by tillage or by a correction of the soil reaction by frequent liming which favours the prevalence of bacterial action. On the other hand, acidity of soils under conifers may make the life conditions for bacteria worse, so that the action of fungi may prevail after that of pedofauna.

In any case, stabilization processes under natural conditions may be very slow. Pine needles and branches on the forest floor under cold climates or plant residues on field surface under arid climates may take dozens of years before stabilization of organic matter is completed.

FIGURE 2
Influence of redox conditions on degradation products of organic wastes (after Sequi, 1989)



However, stabilization processes can be greatly speeded up by realizing the optimum conditions for the activity of microbial populations, so that the whole stabilization takes weeks or months rather than years. These man-made processes firstly replace the action of mesofauna by machines which grind and eventually select the waste components, thus creating optimum conditions for microbial growth. Two main categories of stabilization can be envisaged:

- stabilization in the presence of oxygen, i.e. an aerobic process often called composting;
- stabilization the in absence of oxygen, i.e. anaerobic fermentation, or anaerobic digestion.

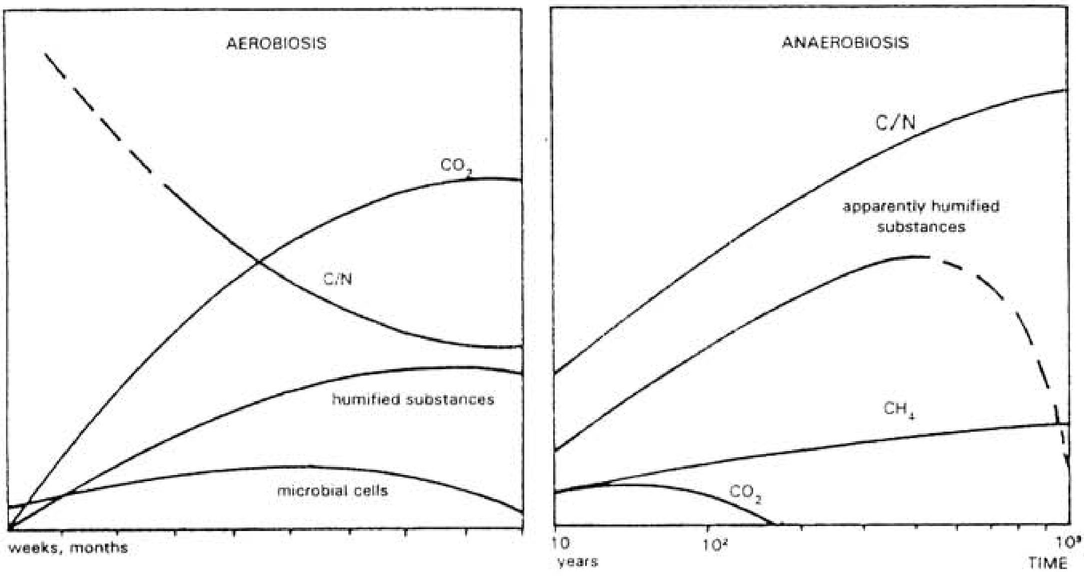
Stabilization of waste organic matter in aerobic conditions is, in fact, carried out with a limited supply of oxygen. If available oxygen is unlimited, any waste could undergo a complete biodegradation. In practice, techniques of aerobic stabilization must provide enough oxygen to the organic waste, e.g. through insufflation of air or by frequently turning the waste mass upside down, so as to prevent the establishment of anaerobic conditions. The product of an aerobic stabilization is often called compost, and a compost is, by definition, the product of an aerobic biodegradation of solid wastes proceeding at an elevated temperature at least during the first thermophilic phase (1-3 days) of the process (Zucconi and de Bertoldi, 1987). The high temperature is provoked by the high rate of degradation of easily decomposable organic compounds. It is important because it leads to 'hygienization' of the waste by killing the pathogenic organisms and sterilizing the seeds present. The end of this phase is characterized by a gradual drop of temperature to a lower stable level which marks the start of the much slower degradation of more complex compounds. This phase is the true stabilization (or 'maturation') of the organic waste, and leads to a progressive increase in humified substances which may take weeks or even months. Aerobic processes cause a strong decrease of the stabilized biomass; about 60% of the organic carbon initially present in the waste may be transformed to carbon dioxide, while the solid compost produced accounts for about 40%. Ammonia and sulphides are oxidized to nitrate and sulphates, respectively, and a great amount of energy is released during the process (Figure 2).

Anaerobic digestion is a process of fermentation which takes place in the absence of oxygen. Ideally a digestion process takes place in a closed vessel, so that the oxygen present is rapidly consumed and micro-organisms, after having reduced other acceptors of electrons eventually available (NO_3^-, Mn^{4+}, Fe^{3+}, SO_4^{2-}), begin to use organic matter in order to obtain the energy which is needed for their life processes. In practice, it is often sufficient for a water layer to submerge the fermenting material in order to shorten the supply of oxygen and cause the start of an anaerobic process. This is what happens in paddy soils shortly after submersion. The organic carbon evolved during the anaerobic digestion is much less than in the aerobic processes, rarely more than 25-30%. Commonly carbon dioxide represents the higher proportion (about 20%) and methane the smaller amount (about 5%). These proportions may reverse in digestions carried out with the purpose of producing methane through a biomethanization process. Most of the organic carbon present in the waste (about 70%) is transformed to organic intermediates, and a very minor amount (5% or less) becomes carbon of living microbial cells. Ammonium and sulphide ions cannot be oxidized, and only a minor quantity of energy is involved to make the life of microbes possible (Figure 2).

It is stressed that, if the overall conditions in which the stabilization processes are not optimized, anaerobic processes are definitely much slower than aerobic processes. Under natural conditions aerobic processes reach an equilibrium between new carbon organization and mineralization that cannot be obtained in anaerobic processes. The most striking difference, analytically speaking, is that the C/N ratio, in aerobic conditions, tends to decrease from 20-30 or more in plant residues to approximately 10 in soil organic matter, while it will markedly increase as a result of anaerobic processes (Figure 3).

In general, the most important difference is that an aerobic process reaches a steady state after some weeks or months, while the course of anaerobic processes may be a question of very long duration. Contrasted ecological conditions play important roles in speeding up, in slowing down or in determining the kind of process which will take place. Under cold humid climates anaerobic transformations will be more frequent than under temperate climates, while the equilibrium of an aerobic process will be determined by the temperature.

FIGURE 3
Trends in the transformation of organic materials under aerobic conditions (after Sequi 1992)



QUALITY CRITERIA FOR ORGANIC MATTER

Methods to assess the quality of organic matter in soils, manures, sludges, composts or other different biomass are still not well defined. Some authors have suggested the use of selected spectral properties of humic substances (e.g., the degree of aromaticity) but found that the nominal molecular weight distribution of humic acids decreases as the degree of humification increases. This is contrary to the normally accepted trend. Humification of soil organic matter has been widely studied using the ratio between humic acids (HA) and fulvic acids (FA), but the results are of uncertain interpretation because they depend on many factors, including even the geographic distribution of the soils. Another common method is the use of the spectroscopic variable that is the E_4/E_6 ratio (the ratio between the absorbance at $\lambda=465$ and $\lambda=665$), which is sometimes considered as an index of humification. However, the addition of a small amount of humic substances (i.e., humic acid from leonardite) is sufficient to change the results completely. The cation exchange capacity (CEC) of the organic fractions has also been used to evaluate the degree of humification of organic amendments but is a very indirect criterion of evaluation (Sequi *et al.*, 1991).

In order to evaluate the stabilization of the organic fraction in sludge, it has been suggested to apply the procedure devised by Schnitzer *et al.* (1981) by which the characterization of soil organic matter is based on the extraction of the soil samples with a solution of sodium hydroxide plus sodium pyrophosphate. The ratio between the extracted and the total organic carbon should give a 'degree of humification'. In preliminary experiments, such a procedure has been found unsuitable for organic wastes, because the quantity of organic carbon extracted depended mainly on the type of waste. The amount of extracted material is very high if the treatment plant collects wastewaters from paper industries. Furthermore, the procedure gives erratic results during maturation of the sludge.

Roletto *et al.* (1985) suggested the adoption of a set of chemical parameters to characterize stabilized organic matter. They include, in addition to the percentage of carbon extractable in pyrophosphate (defined as 'humification ratio'), the humic fulvic acid ratio, nominal molecular weight distribution of the extracts, and a 'humification index', defined as the percentage of humic carbon or total amount of organic carbon. It seems plausible to infer that such chemical parameters are useful to follow compost maturation, but are less useful to compare different composts. The authors, for instance, suggested the use of the minimum value of 3.50% referred to the humification index which, however, ranges from 4.31 to 18.57% among five different composts.

Chanyasak and Kubota (1981) focused their attention on the water soluble phase of the composts, where micro-organisms are actually active. They found that the ratio between organic carbon and organic nitrogen in water extracts of composts was very variable during the first phases of maturation, but decreased to a uniform final value of 4.5 to 6.5 for well-matured composts, regardless of type of starting raw materials. Unfortunately, this ratio is low (5 to 6) even in raw sewage sludges, and this parameter cannot be used to assess a standard measure of maturity for these materials. For similar reasons, other conventional parameters used as indexes of a humification degree (Tsutsuki and Kuwatsuka, 1984) seem to fit the need for a good characterization of humified matter in soil, but not in wastes.

Recently, the use of selective chromatography on solid polyvinylpyrroliddone (PVP) to separate humified from non-humified materials in soil, dung, compost and sludge extracts has been suggested (Sequi *et al.*, 1986; Ciavatta *et al.*, 1988). A scheme of the proposed procedure is represented in Figure 4. At the moment, the use of solid PVP is required by Italian law for characterization of organic amendments (peat, leonardite and humic extracts). The fractionation scheme of organic extracts is very simple, and identical for different matrices (soils, organic fertilizers and amendments, etc.). The separation of humified from non-humified (NH) materials is achieved by precipitation of humic acid (HA) at a low pH and by loading the soluble fractions on columns packed with insoluble PVP. Non-humified materials (NH) are not retained on PVP. After washing with 0.05M H_2SO_4, the fulvic acid (FA) fraction is eluted with 0.5M NaOH and added to the humic acids. This procedure has been applied with good results on organic amendments, and is also used to follow the maturation of organic materials in sludges in compost from urban refuse.

Three new parameters of humification have been proposed:

1. humification index (HI) $\mathbf{HI = NH/(HA+FA)}$

   i.e., the ratio between non-humified (NH) and humified (HA+FA) compounds;

2. degree of humification (DH) $\mathbf{DH\% = [(HA+FA)/TEC] \, . \, 100}$

   i.e., the percentage of humified compounds with respect to total extracted carbon (TEC);

3. humification rate (HR) $\mathbf{HR\% = [(HA+FA)/TOC] \, . \, 100}$

   i.e., the percentage of humified compounds with respect to total organic carbon (TOC) in the sample.

FIGURE 4

Separation of humified (HA + FA) from non humified materials (NH) by means of columns packed with insoluble PVP. Non-humified fractions are not retained on PVP; after washing with 0.005 M H_2SO_4 the fulvic fraction is eluted with 0.5M NaOH and added to humic acids (after Ciavatta *et al.* 1990).

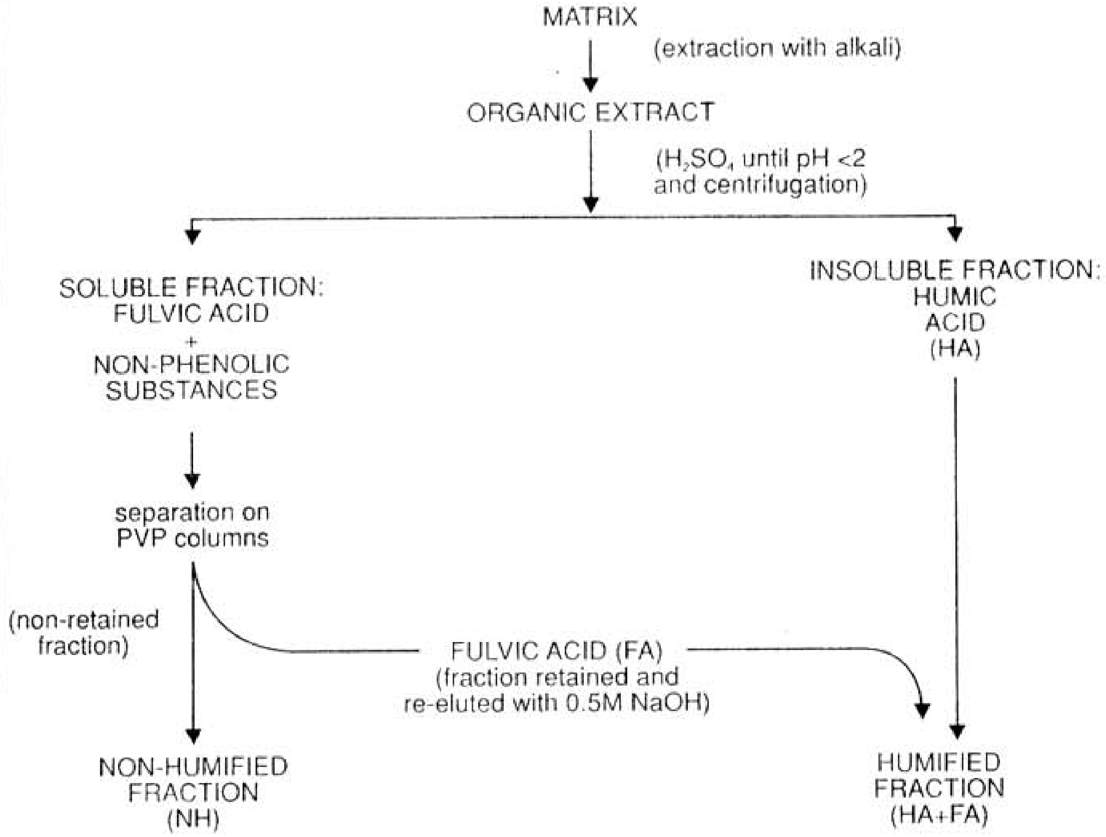


TABLE 1

Humification index (HI), degree of humification (DH) and humification rate (HR) of some soils, organic fertilizers and amendments (after Ciavatta *et al.*, 1990; Benedetti, 1992)

Sample	HI	DH%	HR%
Agricultural land (Tor Mancina)	0.5	68.2	58.2
Forest soil (Tolfa)	0.3	76.5	47.8
Pig manure	0.4	70.5	18.3
Compost of pig manure	0.2	81.1	21.6
Cattle manure	0.2	83.7	25.5
Compost of cattle manure	0.1	86.3	34.2
Leather meal	19.7	4.8	1.6
Peat	0.3	76.9	19.3
Leonardite	0.05	94.9	82.7

In general, the humification index (HI) is near to zero (0-0.5) for humified materials (i.e. soils, organic amendments), and much higher than 1 for non-humified materials (i.e. organic fertilizers, raw composts, sewage sludges and swine slurries). DH is higher than 60% for humified materials (peat); less humified samples (organic fertilizers) show lower DH values. Strongly humified materials such as leonardite also show a high HR (> 80%), whereas this parameter appears to be generally low for soils and organic materials (Table 1). DH has also been used to monitor the evolution of organic matter from animal manure after digestion by earthworms and to evaluate the maturity of compost. The values reported in Table 1 show the increment of DH and HR values after composting.

Although the above methods have been proven to be useful for evaluating the evolution of organic matter from a quantitative point of view, they are unable to distinguish qualitatively organic matter extracted from different sources.

A technique that easily serves this purpose and that, in addition, produces good evidence of the organic matter evolution during humification, is electrofocusing (EF), an extension of the electrophoretic principle. EF is carried out in a polyacrylamide gel tube where an electrophoretic carrier ampholyte has been previously preblended to give a pH gradient from a lower to a higher value. During electrofocusing, each macromolecule moves under an electric potential in search of its isoelectric point.

Since 1972, many authors have used EF to characterize soil enzymes and humic substances extracted from soil, rivers and other organic materials. Although the results of some authors have shown EF to be a reliable method, other authors consider the EF findings as artifacts. In general they believe that separation of the humic substances by the EF technique was caused by their interaction with the carrier ampholytes.

However, the integrity of humic substances during EF application has been demonstrated. It has been assessed that the possible interaction between humic substances and ampholytes is not responsible for the appearance of some bands as artifacts in the gels (De Nobili, 1988). General findings then confirmed that electrofocusing is a reliable technique and can be used successfully to monitor differences in the quality of the organic matter even in raw, non-purified materials. Even when using such materials, interferences are very limited and resolution appears to be satisfactory (Ciavatta and Govi, 1993). Another advantage of electrofocusing is the possibility of demonstrating differences between materials that are apparently very similar from a quantitative point of view if tested by other procedures. For other organic wastes, EF profiles have been suggested to reflect stabilization processes (i.e., humification) of the organic matter on a purely qualitative basis.

The stabilization of organic matter consists of processes similar to humification, and its extent may often be determined by the application of the humification parameters. In general, the evolution of organic matter during maturation of an organic amendment is characterized by a continuous increase in humified or pseudo-humified substances in the alkali-soluble fraction, so that DH effectively represents the development of the process. Sometimes, but not always, the HR value also shows a trend similar to that of DH. Figure 5, for instance, shows the trend of the DH during the organic matter stabilization processes in a compost from urban refuse. The value increases continuously, until it reaches stable values and an asymptotic trend at the end of the stabilization processes, after 40-60 days of composting. In the case represented in the same figure, HR is not correlated to the stabilization of the

FIGURE 5

Trends of the degree of humification (DH) and the humification rate (HR) during the thermophilic phase of the organic matter stabilization process in a compost from urban refuse (after Sequi *et al.*, 1991).

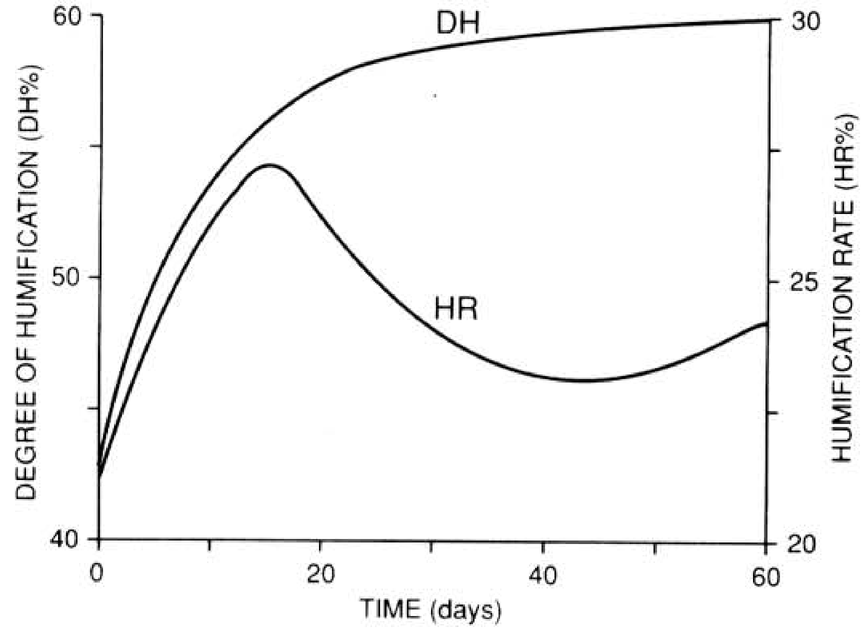
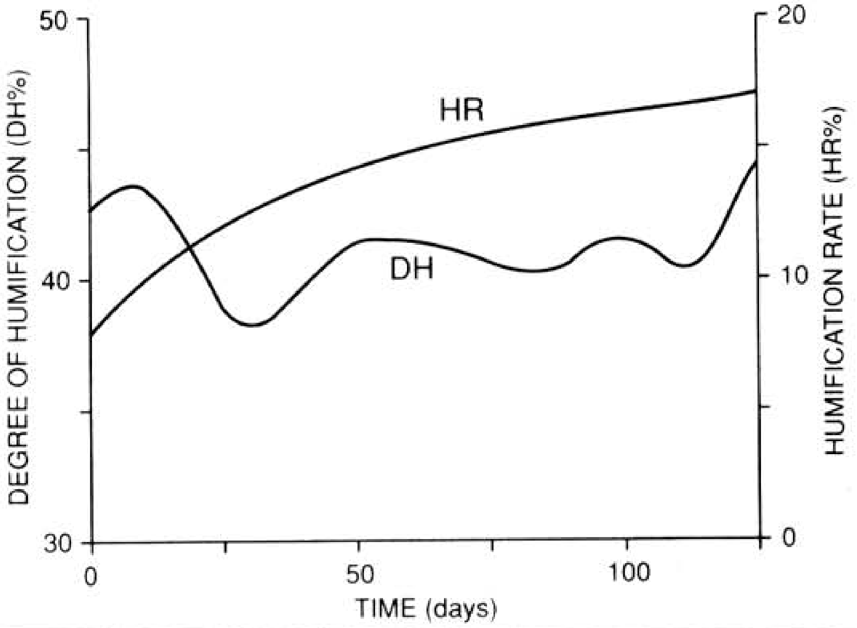


FIGURE 6

Trends of the degree of humification (DH) and of the humification rate (HR) during the stabilization process of pig slurries (after Sequi *et al.*, 1991)



amendment. It must be borne in mind that in some materials there is a continuous and immediate transformation of the substances liberated from an extremely heterogeneous organic matrix, and humic-like substances do not accumulate during the process. In these cases, therefore, only DH is of practical value, because humified materials are of significant importance in extracts but only slightly relevant with respect to total organic carbon. Generally speaking, for the majority of organic substrates, DH and HR change and reflect continuously the evolution of organic matter. For particular matrices such as pig slurries, however, only HR fits in with the actual development of the process, as shown in Figure 6. A better suitability of either DH or HR probably depends on the specific nature of the material considered, i.e., whether the bulk of organic matter in the material is involved in the maturation process or not. If processes are effective for a small proportion of the material and involve progressively only further limited parts while the bulk remains unaltered, DH can describe the process better than HR. Especially in the case of liquid or semi-liquid wastes, however, the entire mass of organic matter is simultaneously involved in the stabilization process. In such conditions, only HR can accurately describe the process.

TURNOVER OF ORGANIC MATTER IN SOIL

In a given pedoclimatic condition, turnover of organic matter in soil is controlled by the kinetics of mineralization rate of organic matter. Mineralization kinetics are correlated to the quality of organic matter and its humification degree.

The mineralization of organic matter added to soil is influenced by the chemico-physical characteristics of soil, but principally by the biological fertility of soil (Benedetti, 1983; Grant *et al.*, 1993). Climate can deeply condition this process, especially in countries in which a large part of the national territory is under a semi-arid climate such as those in Mediterranean areas. Many studies have been carried out regarding the mineralization rate, but only a small part of them is applicable to semi-arid zones and to soils treated with organic materials. It appears difficult to calculate how much nitrogen applied with animal manures will be used by crops, and how much will be lost and pollute either the air with ammonia or nitric oxides or the water with nitrate, ammonia and organic nitrogen compounds.

Amberger *et al.* (1982) affirm that in general the mineralization rate of organic compounds is relatively low (5-20% for years). Other investigations, however, give mineralization rates much higher (up to 60% of the total organic nitrogen) during the same year of application. Actually the mineralization of organic matter applied to the soil can vary greatly. It differs with the kind of manure, with the location conditions (soil, climate, weather), the time of application and the kind of incorporation into the soil (Kirchmann, 1991).

Boyle and Paul (1989) hypothesized that organic residues are composed of more fractions characterized by different stabilities and that the labile fraction of the organic matter added to soil mineralizes quickly. Later the stable fraction shows a slow decline that is described by zero order kinetics. They proposed the following equation in order to explain the phenomena:

$$y = ct + a\,(1-e^{-kt})$$

where y represents the CO_2 developed in the time t, c the zero order constant, a the organic carbon mineralized by a first order kinetics, and k the first order constant.

According to Boyle and Paul (1989) nitrogen mineralization also follows the same trend. In fact two organic nitrogen pools are present in the soils treated by organic amendments, the first one labile and the second one stable. They mineralize by different kinetics. The fast decrease of the ammonium in a treated soil should be due to a net immobilization by micro-organism. Subsequently the high content of organic nitrogen into microbial cells could be mineralized, so that it represents a significant reserve of nitrogen in soil.

An important problem is represented by the difficulty of using provisional statistical models, standardized by laboratory experiments, in order to evaluate the mineralization in field conditions. It can be interesting to refer some observations of Barbarika *et al.* (1985) who carried out a comparison among the results obtained by five different laboratory experiments on the mineralization of organic nitrogen of sludges added to 11 different soils. The mineralization appeared to be influenced by soil characteristics and it was advisable to use a typical K for each soil to describe the mineralization rate. The authors ascribed the different results obtained to differences in the analytical procedures. In fact in some of them a prefixed incubation was carried out with final extraction of nitrogen, while in others the incubation and leaching of nitrogen were effected at fixed times. The different amounts of nitrogen mineralized were probably also caused by a feedback effect from the mineral nitrogen stored. Between the two different analytical procedures, the incubation-leaching was more suitable than the incubation-extraction, because it better simulated the field conditions.

Table 2 clearly shows the influence of soil characteristics, especially of biological fertility, on the turnover of organic matter applied. In fact in the soil with high biological fertility the organic matter mineralized faster than in the other two soils: 1300 ppm of CO2 were produced in 14 days, against 800 ppm and 400 ppm in the medium and the low fertility soil, respectively.

TABLE 2

Total CO_2 evolution in different soil treated by pig, cattle and sheep manure during 14 days. Values are expressed as % of carbon mineralized (after Benedetti 1992)

Sample	High fertility soil	Medium fertility soil	Low fertility soil
Pig manure	18.3	15.2	0.8
Cattle manure	8.3	7.1	2.9
Sheep manure	2.8	2.1	0.9

Values of potential mineralization of organic nitrogen in the high fertility soil from the same experiment (Table 3) show the two different pools of nitrogen mineralized from the organic matter applied. The results also provide an indication of the rate of the release of nitrogen. This aspect is very important in order to rationalize the amount of organic materials applied, as a function of the crop requirements. During the experiment the leather meal released more than 70% of the total nitrogen added during the first two weeks of incubation, while the other products released lower amounts and showed different trends. In some cases (cattle and pig manure), a constant increase in the amount of nitrogen released over time was found, while in other cases (sheep manure) mineralization began only after 8 weeks of incubation.

LOCAL CONSTRAINTS

Many of the above results and most information on turnover of organic materials in soil arise from laboratory experiments. They are undoubtedly valuable, but can be useless from a

TABLE 3

Potential mineralization of nitrogen of high fertility soil treated by pig, cattle and sheep manure. Values are expressed as % of nitrogen mineralized (after Benedetti, 1993)

Weeks **Sample**	2	4	8	12	16	22	30
Pig manure	26.8	14.6	33.8	11.0	6.5	0.4	6.2
Cattle	16.5	27.7	21.1	29.7	1.0	0.7	3.8
manure	0.0	0.0	0.0	3.1	1.2	1.7	4.7
Sheep	71.0	14.0	13.0	2.0	0.0	0.0	0.0
manure	65.0	9.0	4.0	2.0	0.0	0.0	0.0
Leather meal							
Lactic casein							

practical point of view if the actual pedo-climatic conditions in which the organic materials are transformed are not taken into account. Transformations may undergo dramatic changes if climatic conditions vary due to the establishment of differences in the organisms which act in succession on the organic substrate.

The turnover of organic components in soil is also deeply influenced by ecologically contrasted conditions. In fact, transformations of soil organic matter are associated with the activity of soil micro-organisms and soil enzymes. Soil microbial activity and, in part, soil enzyme activity are controlled by physical and chemical conditions of soil such as porosity, oxygen supply, pH and ionic activity. However, the real limiting factors for the micro-organisms are temperature and soil moisture. These parameters are strongly influenced by climatic conditions. For example the mineralization of organic matter in continental regions has its maximum values in summer, whilst in Mediterranean regions maximum values occur in autumn and winter, which reflects the humidity factor of leaf decomposition (Gallardo *et al.*, 1993). Bell (1993), in a study carried out in a high central valley of Mexico, demonstrated the relationship between altitude (assumed to reflect a temperature effect), organic matter mineralization and wheat production. A difference of 500 m, corresponding to an approximate 3°C decrease in average temperature, resulted in a selection in the population of microbes (possibly an increase in the fungi population with altitude) and thus in different rates of mineralization.

When explaining results from areas under ecologically contrasted conditions these alternative possibilities must always be taken into account. Otherwise, if interpretation is taken on the basis of conditions arising in humid-temperature climates, it could be of little value for use in developing countries under arid or semi-arid climates. A different adaptation of some micro-organism groups under different ecological ecosystems should always be postulated. In some cases moisture will be the limiting factor, while in other instances it will be the temperature. So, the first step to rationalize the management of organic matter in the soil is the assessment the actual limiting factor for the activity of micro-organisms. Since the activity of soil micro-organisms is associated with the transformations of soil organic matter, the main constraint for organic matter management is represented by the climatic parameter, i.e. temperature or humidity, which conditions soil life.

Unfortunately, as reported above, most experimental data related to organic matter turnover have been achieved in countries where the limiting factor seems to be temperature rather than humidity. Such data cannot be extrapolated to countries where the limiting factor is humidity. It seems plausible to suppose that in some countries situated in tropical areas neither temperature nor humidity are really limiting the turnover of organic matter. In these conditions the management of organic materials must follow different rules. However, knowledge in this field is rather scanty so that additional research is needed in order to prepare a general code of organic matter management adapted to ecologically contrasted conditions. According to new outlooks on microbial ecology of the soil environment (Parkin, 1993), special attention must be given to its variability in space and scale as well as to the soil environmental factors which control this variability at various scale.

CONCLUSIONS

Nutrient recycling is essential in sustainable agriculture and can be practised only by applying organic waste to the soil, because soil is the natural fate of wastes. Of course, recycling of waste should be based on correct management techniques of organic wastes. Such techniques are not always simple and in general take for granted a high degree of professional experience. Often management and utilization of organic materials is readily avoided by farmers, who favour the exclusive use of chemical fertilizers. However, the integral recycling of waste must at least be encouraged. Even though sustainable agriculture can strictly speaking be practised without the utilization of organic materials, it should be stressed that the recycling of wastes in agriculture is an essential condition for the establishment of a sustainable society.

Stabilization of organic matter in the waste materials and turnover of the organic materials in soil are associated with pedological and climatic conditions. The transfer of the experimental results achieved, e.g. in humid-temperate climates, to areas with arid or semi-arid conditions, is generally misleading.

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Nutrient cycling and nutrient supply in agroforestry systems

Agroforestry is distinguished from other cropping systems by the deliberate integration of woody perennials (trees, shrubs, palms, bamboos, etc.) with crops and/or animals on the same land-management unit. The integration can be either in spatial association or in temporal sequence (Nair, 1989). Spatial associations of trees and crops include hedgerow intercropping (alley cropping), trees on boundaries, trees in cropland, and live fences. Temporal sequences or rotations of trees and crops include improved fallows.

Growing trees in either association or rotation with annual crops or pastures is generally perceived to have beneficial effects on soils (Sanchez, 1987). The hypothetical benefits include (i) pumping up of nutrients from subsoil by deep-rooted perennials, (ii) reduction in leaching losses through the capture of mobile nutrients by the well-developed rooting systems of perennials, (iii) maintenance of soil organic matter through the supply of above- and belowground litter and prunings from perennials, (iv) addition of nitrogen through biological nitrogen fixation by perennials, (v) protection from soil erosion, and (vi) maintenance or improvement of soil physical properties (Young, 1989).

The objective of this paper is to review the literature on the potential role of trees in (i) cycling nutrients to crops and pastures through pumping up of nutrients from subsoil, (ii) reducing nutrient losses by leaching, and (iii) increasing the availability of nutrients through maintenance of soil organic matter.

Although agroforestry has been proposed to have most potential in 'marginal' areas where monocultural agriculture and forestry may not be most feasible or desirable (Nair, 1984), most examples of successful agroforestry systems are from areas dominated by base-rich, naturally fertile soils (Sanchez, 1987; Szott *et al.*, 1991a). This review will examine contrasts in nutrient cycling and supply between relatively fertile and infertile soils.

NUTRIENT PUMPING

A frequently cited hypothesis for the benefit of integrating trees with crops or pastures is the pumping up of nutrients from subsoil by trees. This hypothesis is based on the belief that trees have deep, spreading root systems capable of absorbing nutrients from a greater soil volume than annual crops. According to the hypothesis, nutrients absorbed by trees from

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PAPER 2.5

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outside the effective rooting zone of annual crops are eventually deposited in or on the surface soil via root and leaf litter, nutrient leaching from the tree foliage, and prunings of tree leaves and branches. These nutrients can then be utilized by annual crops growing either simultaneously or in sequence with the trees.

The ability of a tree to absorb nutrients from outside the soil volume exploited by roots of annual crops depends upon its spatial distribution and temporal patterns of root growth. At any given tree age, the spatial distribution of roots can vary with provenance (Vandenbeldt, 1991) and species (Ruhigwa *et al.*, 1992; Stone and Kalisz, 1991). An aim of improved systems with simultaneous associations of trees and crops is thus to select species and management that fully exploit the soil volume for growth resources, while minimizing competition (Anderson and Sinclair, 1993). Van Noordwijk (1989) conceptualized that the 'ideal' root system for a tree growing with crops had deep roots for nutrient pumping and limited horizontal development in order to minimize competition with crop roots. The roots of trees grown in monoculture frequently do not conform to this 'ideal' (Jonsson *et al.*, 1988), but mixtures of trees and crops may exhibit more niche differentiation than expected from observations of root architecture for trees grown in monoculture (Anderson and Sinclair, 1993; Kang *et al.*, 1985).

Tree roots can undoubtedly extend deep into soil and extract resources from beyond the rooting depth of annual crops, as evidenced from deep soil uptake of water (Stone and Kalisz, 1991) and stable strontium tracer (Van Rees and Commerford, 1986). The extent to which tree roots in deep soil layers contribute to the overall uptake of nutrients is, however, less clear. Results from a multilocational study in which radioactive phosphorus was injected at varying soil depths and distances from the stems of banana (*Musa* spp.), cocoa (*Theobroma cacao*), coconut (*Cocos nucifera*), coffee (*Coffea arabica*), and oil palm (*Elaeis guineensis*) indicated that highest root activity for all these perennials was near the soil surface and close to the plant even when soil conditions were ideal for extensive root development (IAEA, 1975). In those studies of uptake from greater than 1 m depth, up to 14% of the total phosphorus uptake by coffee from within the top 1.8 m occurred from 1.2 to 1.8 m depth, and the fraction was strongly dependent on the season. Up to 4% of the total phosphorus uptake by oil palm from within the top 1.5 m occurred from 1.5 m depth.

The limitation of nutrient uptake in surface soil can enhance nutrient uptake from subsoil. Water stress, for example, in the surface soil can increase the importance of the subsoil as a source of nutrients for perennials with root systems established in both the surface soil and subsoil. The relative importance of subsoil as a source of nutrients can increase during long, seasonal dry periods (Commerford *et al.*, 1984; Eastham *et al.*, 1990). Such observations suggest that, in the absence of soil restrictions to root growth, the exploitation of deep soil layers by trees may be greater in seasonally dry environments such as the semi-arid tropics than in environments with only brief dry periods such as the humid tropics.

Because the demand and uptake of nutrients by trees is strongly related to their growth, it follows that subsoil nutrients may be relatively most important for early tree growth. Young trees require nutrients from soil because their demand for nutrients can not be met by the supply in litterfall and leaching from tree foliage. As trees get older the demand for nutrients decreases and litter can gain importance as a source of nutrients (Bruijnzeel, 1990).

A decrease in nutrient demand may not occur, however, if nutrients are exported in harvested tree products such as fruits (Atkinson, 1986).

The greatest potential for nutrient pumping exists on soils with high concentrations of nutrients in the subsoil and with no chemical and physical barriers to root penetration. The potential for nutrient pumping in acid, infertile soils can be limited by chemical barriers to root penetration, such as high aluminum saturation and low levels of phosphorus and exchangeable bases in the subsoil, and by lack of weatherable minerals in the subsoil (Szott *et al.*, 1991a). The selection of tree species adapted to the soil chemical and physical constraints is an obvious requirement for effective nutrient capture and cycling. In rotational systems, the roots of trees that penetrate into subsoil with high aluminum saturation and low available nutrients can create root channels, which the roots of subsequent crops may follow into the subsoil (van Noordwijk *et al.*, 1991).

NUTRIENT LEACHING

Leaching losses, in principle, depend on the amount of water moving through soil, the nutrient concentration in the soil water, and the retardation of the nutrient to movement. Leaching can occur under conditions of net downward water movement through the soil and of nutrient supply in the soil exceeding nutrient demand by plants. The nutrients most affected by leaching are nitrate, potassium, calcium and magnesium. The leaching of nitrate can accelerate the downward loss of calcium and magnesium, which leads to acidification of soil (Cahn *et al.*, 1993).

In agricultural systems with annual crops, active rooting and plant demand for nutrients occur seasonally. Nutrient supply in the soil typically exceeds plant demand at the start of the growing season. On acid soils in high rainfall environments, the rooting depth of annual crops may also be insufficient to capture leached nutrients (van Noordwijk, 1989). Perennials with their permanent, well-developed rooting system and their demand for nutrients both between crop growing seasons and during early crop growth can presumably minimize the accumulation of leachable nutrients in soil.

Results from several studies indicate that agroforestry systems can reduce leaching losses. Imbach *et al.* (1989) measured nutrient concentrations in soil water at 1 m depth and estimated percolation from a hydrological balance model in order to calculate leaching loss from systems of cacao (*Theobroma cacao*) grown below the shade of either *Cordia alliodora* or *Erythrina peoppigiana*. Annual leaching losses of nitrogen (5 kg/ha), phosphorus (0.5 kg/ha), and potassium (1.3 kg/ha) were small and similar in both systems. Annual leaching losses of calcium and magnesium were higher from the *T. cacao-E. poeppigiana* system (27 and 20 kg/ha, respectively) than from *T. cacao-C. alliodora* (6 and 6 kg/ha, respectively). Seyfried and Rao (1991) directly compared leaching losses from monocropped maize and a mixed perennial system of *T. cacao*, C. alliodora, and plantain (*Musa* spp.). Leaching losses during 242 days were dramatically less from the perennial system than from maize for nitrogen (1 and 57 kg/ha, respectively), potassium (1 and 3 kg/ha, respectively), magnesium (3 and 21 kg/ha, respectively), and calcium (3 and 43 kg/ha, respectively). Horst *et al.* (1991) found that *Leucaena* reduced leaching losses in a hedgerow intercropping system through its higher root densities, as compared to maize and cassava, in the subsoil.

Van Noordwijk (1989) used the excess of rainfall over evapotranspiration and constants for retardation of nutrient movement in order to calculate the rooting depth required to intercept leaching nutrients. He concluded that deep-rooting plants are required in each crop growing season to minimize losses of highly mobile nutrients, such as nitrate, on acid soils in the humid tropics. In other words, spatial rather than sequential associations of trees and crops would be required. Based on his model, sequential systems of crops followed by deep-rooted perennials to recover nutrients leached to the subsoil during the crop phase would effectively minimize leaching losses in lower rainfall environments, such as the sub-humid tropics.

Acid subsoils rich in aluminum and iron oxides and low in organic matter can have significant anion exchange capacity, which enables them to retain leached nitrate (Cahn *et al.*, 1992). Deep rooting perennials may be more effective than annual crops in exploiting this sorbed nitrate. Schroth (1989), in research on soil with an acid subsoil containing appreciable anion exchange capacity, observed that tree roots but not crop roots were able to penetrate the compact subsoil and take up sorbed nitrate. Enrichment of the subsoil with organic matter from tree roots, on the other hand, may reduce the anion exchange capacity (Cameron and Haynes, 1986).

In spatial associations of trees and crops, the roots of the trees and crops can exploit the same volume of soil and potentially compete for nutrients. The competition between root systems for resources is more likely for water and mobile nutrients such as nitrate than for less mobile nutrients such as potassium and phosphorus (Gillespie, 1989). Moderate competition between trees and crops for water and nitrate might in certain situations have beneficial effects on nutrient cycling. The loss of nitrogen via denitrification, for example, requires a supply of soil nitrate and a lack of soil oxygen. Increased plant uptake of nitrate and water, particularly in high rainfall environments, could conceivably reduce the potential for denitrification through reduction in soil nitrate and improvement of soil aeration in the root zone (Grimme and Juo, 1985). Symbiotic nitrogen fixation decreases with increasing nitrate (Herridge and Bergersen, 1988); it therefore follows that exploitation of soil nitrate by a non-nitrogen fixing plant component in a spatial association of trees and crops could conceivably enhance biological nitrogen fixation by a nitrogen fixer.

Leaching of nutrients is reduced when water infiltrates through soil cracks or macropores, bypassing the bulk soil containing the nutrient (Grimme and Juo, 1985). Channels left in soil by dead tree roots may increase bypass flow (van Noordwijk *et al.*, 1991). It therefore follows that leaching losses may be reduced following the tree phase in agroforestry systems as a result of increased bypass flow through old tree root channels.

SOIL ORGANIC MATTER

Low input agroforestry systems have the potential to equal natural ecosystems in rate of carbon and nutrient accumulation in aboveground biomass (Sanchez *et al.*, 1989). Carbon and nutrients in the perennial component of agroforestry systems can be cycled within the system through root litter, aboveground litter, and prunings. Alternatively, carbon and nutrients in the perennial component can be exported in harvested products such as fruits, fodder, poles, and fuelwood. Some nutrients exported in fodder conceivably could be returned to the system as animal manure.

Growth of trees can reportedly maintain or increase the organic carbon content of topsoil in hedgerow fallow systems (Ruhigwa *et al.*, 1993), in improved fallow systems with nitrogen fixing perennials (Gichuru, 1991), and in hedgerow intercropping (Yamoah *et al.*, 1986). Maintenance of soil organic carbon in hedgerow intercropping normally requires retaining tree prunings in the system rather than removing them from the system (Kang *et al.*, 1985). Organic carbon content of topsoil has been observed to be higher under the canopy of isolated, mature trees than in adjacent open grassland (Belsky *et al.*, 1993).

The effect of trees on soil organic carbon, nonetheless, varies among tree species and may not be directly related to the effects of the tree on crop yield. Yamoah *et al.* (1986), for example, observed an increase in soil organic carbon under *Cassia* but a decrease under *Flemingia*. Soil organic carbon increased more under *Cassia* than under *Gliricidia*, presumably due to the slower decomposition rate for *Cassia*. Gichuru (1991) reported statistically similar soil organic carbon contents following fallows with *Cajanus cajan* and *Tephrosia candida*, but maize yield was significantly higher following the *T. candida* than the *C. cajan* fallow. The difference in residual affect was attributed to less woody material and more rapidly decomposable leafy material in *T. candida* than *C. cajan*.

Little relationship typically exists between total soil organic matter content and crop productivity (Sanchez and Miller, 1986). This implies that the importance of the perennial component to crop productivity is more related to its effect on the various soil organic matter fractions than on total soil organic matter (Sanchez *et al.*, 1989). Fractions of organic matter differ greatly in their role in nutrient release (Parton *et al.*, 1987), and techniques are being developed to characterize better the effects of management systems on functional pools of soil organic matter (Christensen, 1992).

NUTRIENT AVAILABILITY

The release of nutrients from tree litter and prunings (Tian *et al.*, 1992) can partially meet the nutrient requirements for moderate levels of crop production on fertile (Glover and Beer, 1986) and infertile soils (Szott *et al.*, 1991b). The recycling of phosphorus through tree litter and prunings to associated crops is, however, typically inadequate to meet crop demands (Szott *et al.*, 1991b). Leaf litter quality is generally lower and decomposition slower on acid, infertile soils than on relatively more fertile soils (Vitousek and Sanford, 1986).

Roots play an important role in nutrient cycling in tropical forests (Noij *et al.*, 1993). In agroforestry systems the decomposition of fine tree roots may be an important source of nutrients, especially because the release of available nutrients occurs within the crop rooting zone. In a review of literature, Szott *et al.* (1991a) concluded that the fine root biomass of agroforestry systems tends to be less than for tropical forests but slightly larger than for annual crops.

Phosphorus is frequently the most limiting nutrient in the humid tropics (Noij *et al.*, 1993). The integration of perennials with crops could increase the total quantity of phosphorus in the system through either reduction of soil erosion or 'pumping' of phosphorus from outside the crop rooting zone. Otherwise, perennials simply enhance the transfer of phosphorus from soil to vegetation. The internal cycling of phosphorus through tree litter and prunings may increase phosphorus availability, without increasing total quantity of phosphorus in the system, by converting recalcitrant inorganic forms of soil phosphorus taken up by trees to organic forms (Palm *et al.*, 1991). Organic phosphorus is an important source of phosphorus in acid, infertile soils; and the integration of trees in cropping systems offers potential to increase pools of organic phosphorus (Tiessen *et al.*, 1992).

In addition to supplying nutrients to crops, the litter and prunings from perennials may play a role in detoxification of soil aluminum and enhancement of soil biological activity. The mechanism for aluminum detoxification is believed to be a decrease in monomeric aluminum activity, resulting from the precipitation of soluble aluminum and complexation of aluminum by organic matter (Bell and Bessho, 1993). Hauser (1993) observed that hedgerow intercropping can increase the activity of fauna, thereby enhancing the cycling of nutrients.

NUTRIENT EXPORT

The processes of nutrient cycling in agroforestry systems are similar to those in natural forest ecosystems; however, in agroforestry systems considerable quantities of nutrients can be exported in harvested crop and tree products. An increase in crop production with an agroforestry system as compared to a monoculture agricultural system can increase nutrient export and lead to a decline in soil fertility unless nutrients are added to the system.

The addition of tree prunings in hedgerow intercropping systems on an acid, infertile soil did not prevent a decline in soil exchangeable cations, soil available phosphorus, and crop yield (Salazar *et al.*, 1993; Szott *et al.*, 1991b). On a more fertile, base-rich soil the application of nitrogen fertilizer was necessary to sustain crop yields in hedgerow intercropping systems (Kang *et al.*, 1985).

In many agroforestry systems a portion of the perennial component may have economic value and hence be removed from the system. The prunings of some trees, for example, have more economic value as animal fodder than as green manure (Kang *et al.*, 1990). The export of nutrients in harvested parts of the perennial component can lead to a decline in soil fertility, resulting in the need for nutrient inputs or fallow periods to sustain productivity.

CONCLUSIONS

Substantial quantities of nutrients can be exported in harvested products from agroforestry systems as from agricultural systems. Agroforestry systems, however, have potential through the presence of perennials to increase the supply and availability of nutrients in the crop rooting zone. Nutrient supply can be increased through the reduction of leaching losses and the pumping up of nutrients from outside the crop rooting zone. The availability of a given supply of nutrients can be increased by the cycling of nutrients through tree litter and prunings. The beneficial effects of trees on nutrient supply and availability can potentially increase the amount of nutrients that can be exported from the system through harvested product and increase the efficiency of production per unit of external nutrient input to the system.

The ability of agroforestry systems to enhance nutrient supply and availability is soil dependent. In soils where nitrogen is the nutrient most limiting crop production, agroforestry systems may increase the total quantity of nitrogen in the soil-plant system through enhanced biological nitrogen fixation and reduced losses, particularly leaching. The cycling and availability of phosphorus and basic cations will, however, greatly depend on the existing reserves of these nutrients in the soil. The ability of agroforestry systems to increase phosphorus availability is largely related to the conversion of phosphorus from recalcitrant inorganic forms to organic forms. When designing and evaluating agroforestry systems it is, therefore, essential to first identify the major soil constraints for a specific area (Sanchez, 1987).

Szott *et al.* (1991a) concluded that the ability of agroforestry systems to enhance nutrient availability is greater on base-rich, fertile soils than on acid, infertile soils. The ability of agroforestry systems to reduce nutrient losses, however, is potentially great on both fertile and infertile soils.

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Role of fallow in cropping systems of dry and humid African savannahs: maintenance of soil fertility and plant nutrient supply in crop rotation

THE CONCEPT OF FALLOW IS COMPLEX AND THE FINDINGS OF RESEARCH IN TROPICAL AGRICULTURE ARE INSUFFICIENT

Fallows have been implemented for ages by farmers all over the world in order to restore the production capacity of cropped areas. However, a wide diversity of practices and management are covered by the concept of fallow. In fact, the impact of fallow on crop rotation, within a given ecological context, depends on the objectives and working means of the farmers. Prof. M. Sebillotte (INRA, France) has proposed the following agronomic definition of fallow:

> "Fallow is the state of a plot between crop harvesting and planting of the next crops. Among other features, fallow is characterized by its duration, by the cultivation techniques applied, and by its impact on the agronomic properties of soils."

Prof. Sebillotte has proposed a methodology to analyse the effects of fallow on the productivity of crops in cropping systems, in terms of the direct impact of fallow on the next crops and of the long-term impact of fallow periods in crop rotation. This methodology will be followed here.

When assessing the impact of a fallow period, it is important, first of all, to make a sufficient description of the parameters of the agro-ecological conditions, of the development of the vegetation and crops during the crop rotation, and of the cropping techniques. The analysis has to be made, starting from the cropping season before the fallow period to the cropping season following fallow in the crop rotation, as far as the impact of the fallow period can be identified. The impact of the fallow period is mainly evaluated through the difference of crop yields observed between a crop rotation with fallow and a similar crop rotation without fallow, maintaining all conditions at the same level.

For the time being, in tropical and Mediterranean countries, most research programmes and publications related to the analysis of the impact of fallow in crop rotations are incomplete, or the conditions of the experiments are not sufficiently documented. Therefore, it is not possible yet to identify the main mechanisms regulating the functions and impact of fallow nor to

PAPER 2.6

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conclude, from such a theoretical approach, on recommendations with respect to fallow techniques in different ecological and farming conditions. Therefore, this paper will be limited to a synthesis of the available documentation regarding the impact of a fallow period on soil biology, soil chemistry and soil physics in some contrasted tropical conditions. It is not possible nowadays to analyse the impact of fallow on the productivity of crop rotations, on the sustainability of cropping systems, on the productivity of farming systems and on the management of natural resources in watersheds, or in villages or territories. Most of the bibliography analysed concerns Western and Central Africa.

Two main agronomic conditions corresponding to contrasted tropical conditions should be distinguished:

- fallow in dry and humid savannahs,
- fallow in humid forest areas.

Dry and humid savannahs, which will only be considered here, have a rainfall pattern of 300-1200 mm rain per year within one rainy season, lasting 2-5 months. For centuries, these areas have been under the pressure of bush fires and grazing in traditional livestock systems. Natural vegetation and soil fertility are therefore widely influenced by the cumulative impact of land use management. The humid forests considered here have an annual rainfall over 1200 mm. These areas have been more or less influenced by shifting cultivation. In fact areas occupied by primary forests are limited to Gabon, South Cameroon and the central part of Zaire. In dry and humid savannahs, in large parts of Zaire and Congo, and in most East African countries, the population growth rate is high and the available arable land *per caput* has decreased rapidly during the last 40 years. Thus, the duration of long-term fallow has recently been severely reduced. Particular attention will be paid to the problems generated by this drastic reduction of fallow periods.

This paper does not consider 'bare fallow' and 'tilled fallow', implemented within 'dry farming' systems, nor fallow in mountainous areas of the tropics, in which a temperate season occurs, and fallow implemented in irrigated areas.

TYPES OF FALLOW IN DRY AND HUMID SAVANNAHS

Three types of fallow should be distinguished within the dry and humid savannah areas:

- fallow during the dry season;
- fallow during the rainy season (usually called 'annual fallow');
- fallow implemented over several years.

Fallow during the dry season

Most of the cropped land in dry and humid savannahs is under fallow during the dry season, which lasts 5-10 months. The biomass from crop residues is then associated with post-cropping weeds. Shrubs and trees grow frequently in the fields. Thus, the composition of the biomass during the fallow period is heterogenous. Additionally, within the same field, the biomass present during a fallow period is highly variable from one year to another, depending on the climatic conditions of the cropping season and of the dry season, on the use of the biomass for fodder or for grazing, and on the collection of fuelwood.

The availability of the biomass during the fallow period determines the activity of the soil fauna and the availability of plant nutrients for the next crops. This biomass regulates wind erosion and the sedimentation of dust, influencing further the availability of plant nutrients. In Northern Burkina Faso, from 1.9 t/ha of millet straws, only 10% are available at the end of the dry season, 30% are destroyed by termites and 60% by roaming cattle and consumed by bush fires. During the dry season in Northern Senegal, the growth of bush trees (*Guiera Senegalensis*) regularly distributed in cropped areas has been evaluated at 225 kg/ha of fuel wood and 400 kg/ha of leaves (DM) returned to the field during land preparation. The contribution of the population of a leguminous tres (*Acacia albidas*) has been quoted in Senegal on millet yields. With a control level of 650 kg/ha of grains, 5 trees/ha provide 3% additional yield, and 33 trees/ha provide 20% additional yield. The impact of *Guiera Senegalensis, Pilostygma* and *Calotropis* has been noted but not evaluated. The impacts of land clearing, cropping techniques and crop residue management on the soil fauna and on the characteristics of soil fertility after the fallow of the dry season are not documented.

Fallow during the rainy season

Fallows implemented during the rainy season are in many areas a method for regulating the cropped areas according to the availability of agricultural inputs: labour force, tools, draught animals, seeds, etc. Even when the population is over 80 people/km^2 in areas in Sudan, such fallows may reach 20% of the arable land. The impact of livestock and fodder management can be very important on the efficiency of such fallows to improve soil fertility. In particular, some ethnic groups have one part of these fallows regularly manured by their herds during the rainy season, while manuring is applied on selected cropped areas during the dry season. However, the impact of differing management on crop yields is insufficiently documented. As the natural biomass of such fallows can be over 4 t/ha in Sudanese conditions, these fallows are in most cases set on fire at the end of the rainy season, thus limiting their role in providing organic material to the soil. Farmers do not have the required energy and tools for ploughing this material in the soil.

Fallow implemented over several years

The main function given by the farmers to this type of fallow is the improvement of soil fertility. However, in many situations, especially in the rainy regions, such fallows are also implemented in order to get rid of weeds (*Imperata cylindrica, Cyperus rotendus*). In the areas receiving more than 700 mm of rain per year, the evolution of the vegetation during the fallow period may be simplified as follows:

- recent fallow (1-4 years): annual graminae and weeds (*Eragrostis* and *Digitaria* in the north of African savannah; *Euphoria, Borreria, Pennisetum* and *Imperata* in the south);
- medium-term fallow (5-15 years): *Andropogons* take place rapidly (especially *gayanus*), creating a major perennial biomass, and shrubs invade the area;
- long-term fallow (over 15 years): edaphic graminae take over from *Andropogon gayanus* with *Hyparrhenia* and other *Andropogon* species, which farmers consider as the signal for new cultivation. The regeneration of the ligneous strata is accelerated in general as of the 10th year.

The rhythm and the importance of the colonization by natural species depends heavily on the soil type, on the water supply (runoff balance), and on the degradation of the land during the cropping period. Publications on the process of recolonization of cropped areas during long-term fallows are scarce. Particular emphasis is put on the detrimental effect of bush fires, on the favourable effect of limited clearing of bush trees during the cropping period, and on the reconstitution of the natural vegetation. Picking out the stocks of shrubs and trees is particularly detrimental.

A much better impact of long-term fallows on soil fertility (physical properties) could be obtained if the present traditional practices of livestock management systems and forestry management were improved. Overgrazing of these fallows is advantageous for leguminous herbaceous species producing limited biomass, but it is not very favourable for enhancing the activity of the soil fauna. In the driest areas, overgrazing may reduce the impact of the shrubs on the regeneration of the soil fertility. Thus, fodder production of a fallow depends much more on the management through grazing than on its stage of evolution towards natural savanna. The biomass production of a long-term fallow depends heavily on available rainfall and on soil conditions. In protected fallows, 6-15 tons of fuelwood can be produced in 4-6 years in South Senegal, corresponding to 3-5 t/ha of annual litter from leaves; 2-8 t/ha of straws may be obtained in Central Burkina Faso. These raw materials are of interest for poor farmers but in most cases they do not belong to the farmers who cultivate the land. Thus, the protection of this biomass for agronomic purposes is frequently socially unacceptable.

AGRONOMIC IMPACT OF LONG-TERM FALLOW

Impact of fallow on soil organic matter content

Soil fertility in dry and humid savannahs depends largely on:

- the dynamics of organic matter in soils;
- the biological activity;
- the interactions between soil biology, soil organic matter and soil clay.

All these factors are influenced by the water regime of soils, depending on the supply of water by rainfall, on the infiltration of the rain in soils and on the water movements in the landscape (shortage or supply of water through runoff). Fallows influence the agronomic properties of soils by providing organic material, restoring the activity of soil biology, modifying (and generally improving) the infiltration of water, and reducing runoff. It is extremely difficult to separate these various fallow effects. In addition, the vegetation of a long-term fallow is often sufficient for taking advantage of water and sediments provided by fields located on the upslope. Thus, proper fallow management in the landscape may efficiently contribute to water and plant nutrient harvesting. Alternative fallow positions and cropped areas along parallel strips have been attempted successfully in this respect in Central Togo.

From available publications, it appears that fallows of a duration of less than 5 years have no significant impact on soil organic matter content. In this respect the impact of long-term fallows is more important on loamy soils than on sandy soils, and more significant on loamy clays than on loams. However, 5-10 years of continuous cropping may reduce the organic matter content of the soil by 30-40% after a long-term fallow, thus undoing the favourable effect of the fallow period. As the herbaceous fallows produce 6-8 times more roots than annual crops, this biomass creates an abundant source of organic material, with rapid decomposition (2-3 t/ha) in sandy soils, which is quite favourable for the first crops after fallow, in particular with regard to nitrogen supply. In soils with a more significant clay content, fallows have a favourable effect on organic clay and organic silt fractions which, because of their low turnover (40 years), have an important positive effect on the soil structure. In a long-term fallow, the biomass of the roots, trees and shrubs can reach 20 t/ha, of which ligneous species may contribute up to 13 t/ha in very humid savannahs. In areas in Sudan, long-term fallows may provide 8-10 t/ha of organic material per year, while 4-5 year fallows, if correctly protected, may provide 4-5 t/ha of organic material per year. Grazed fallows cannot provide more than 2 t/ha of organic material to the soil per year. Even though short-term fallows do not modify the soil organic matter content, they significantly improve the cation exchange capacity and the exchangeable cation content of the topsoil. In Sahelian areas, 10 years of a well-protected fallow may have an effect comparable to the supply of 20 t/ha of manure every three years on continuous cropping. Both techniques are of course not relevant for the improvement of soil fertility in the prevailing conditions of the available arable land *per caput*.

In tropical conditions, there are very few in-depth analyses of the impact of a small improvement of soil organic matter content of the topsoil on the nutrient cycles, on the immobilization of nitrogen, and on the transfer of nutrients from non-available to available status. The mechanisms involved in the implementation of long-term fallows are not sufficiently understood today, and extrapolation of the results obtained in a limited number of sites and conditions is not feasible.

Impact of fallow on soil physics and on the activity of soil fauna

The improvement of soil physics and of the stability of soil aggregates, after a sufficiently fallow period, is well documented. Maximum stability is obtained after a fallow period of 10 years in soils permanently cropped during a long period. The permeability of the topsoils is significantly improved through fallows implemented in sandy soils during less than 5 years; however, the shorter the fallow period, the shorter its effect. Precise observations on loamy clay soils in humid savannahs prove that if the soil structure is very degraded by long-term cultivation, the vegetation has some difficulties for settlement at the beginning of the fallow period. Restoration of the soil physical properties may take several years.

All interventions limiting the activity of the soil fauna (ploughing, burning and harvesting of biomass) severely reduce the efficiency of the fallow in restoring soil physics. However, the benefits from activating soil macro-fauna are still controversial. Some termites have a favourable action on the surface porosity of soils, while others are active factors of soil crusting. The activity of earthworms is more favourable, but needs at least 800 mm of rainfall per year. Like some termite species, they contribute to the humidification of fresh organic matter and create a significant transfer of the deep soil horizons to the soil surface (800-1250 tons of soil/ha/ year). Thus, in humid savannahs, rooting systems and soil macro-fauna contribute widely to the maintenance of soil organic matter and of soil structure. The favourable effect of mulching crop residues and short-term fallows could be related to these factors in some instances. However, the mechanisms involved, the balance sheets of organic matter in different fallow systems and the various levels of activities of soil fauna are not properly documented.

Impact of fallow on plant nutrient availability

The tillage and cropping of a recently cleared area accelerate the mineralization of soil organic matter, thus increasing the availability of nitrogen for crops and probably the availability of sulphur and phosphorus from organic sources. However, comparative plant nutrient balance sheets in cropping systems, with and without fallows, are very few. In Burkina Faso, a precise balance sheet shows that short-term fallow only contributes to trapping the supply from rain and dust. Upwelling of plant nutrients from the subsoil is very limited. Long-term fallows could have a favourable impact on exchangeable calcium and magnesium in the topsoil.

Impact of fallow on weed management in cropping systems

In savannahs, the dynamics of colonization by weeds is slower than in forest areas. However, the degradation of soil fertility under continuous cultivation creates favourable conditions for the development of weeds. As crops get weaker, when the availability of nutrients decreases, weeds are more competitive, being less dependent on nutrient status. Furthermore, farmers prefer to weed the most productive fields first and more intensively. For both reasons, the pression of weeds is higher after long cropping periods than just after clearance of the land. Insufficient weeding creates favourable conditions for the build-up of the stock of seeds from weeds. Fallow is an efficient technique for controlling infestation by weeds. However, if a fallow is overgrazed or regularly set on fire, the weeds overcome the natural vegetation which resettles the field.

IMPROVEMENT OF THE AGRONOMIC IMPACT OF FALLOW THROUGH FALLOW MANAGEMENT AND PREPARATION TECHNIQUES AFTER FALLOW

Setting fire to fallow after two or three weeks of dry season is the most economic way of clearing land. It may be the only way if long-term fallow is composed of ligneous species and spiny species with rapid growth. However, the destruction of the root stock is always a problem. This cannot be avoided if the land is to be ploughed. Ploughing a fallow, even after cutting the stalks and straws, is often beneficial when the biomass is not dried up. However, the draught power required is important, and a minimum level of motorization is required. At least 5 cm of soil need to be ploughed in order to recover the 2 t/ha of dry matter from the biomass of the fallow. Hence, heavy biomass from fallow cannot be ploughed in soils having a shallow topsoil, without mixing sterile subsoil with fertile topsoil. Mulching the biomass of the fallow, broken down into small pieces by a rotator, is an excellent solution. This practice obviously requires power but much less than the power required for ploughing. Direct sowing on mulches has been successfully implemented on large areas in Brazil. The duration of fallow should then not allow a significant growth of shrubs. In the semi-arid tropics, regular setting of trees in the field (especially *Acacia albida*) is very favourable to crop growth and limits erosion. The management of fire for the reduction of the biomass of fallow is then quite delicate.

Several techniques have been elaborated for the improvement of the efficiency of fallow toward soil fertility restoration. All of them aim at accelerating or increasing the regeneration of the vegetation. The most promising technique consists of transforming fallow into temporary pasture, with a thorough control of livestock charge and grazing. In the Sahelian zones of the Sudan, the association of selected ligneous species (*Acacia nilotica* and *Dalbergia sissoo*) with the natural herbaceous cover is highly profitable (2 t/ha of fodder, compared to 1.2 t/ha on control). However, the development of artificial pastures is facing major social constraints in Africa. Artificial pastures may provide nitrogen for the next crops but do not restore soil fertility, if not maintained for at least five years.

Evaluation of the potential contribution of organic sources of nutrients to crop growth

The target of integrated nutrient management is to maintain stable nutrient cycles in the long term whilst supplying sufficient nutrient to production in the short term. Organic matter management is an essential component of these strategies because organic inputs can help to ameliorate a range of system constraints in addition to contributing to the primary target of nutrient supply (Figure 1). Examples of these effects are the contribution of carbon to soil organic matter synthesis and improvement of soil structure through stimulation of the burrowing activities of soil fauna.

Appropriate strategies for organic matter management (OMM) are dependent on the climatic and edaphic characteristics of an area, and the socio-economic circumstances of the farmer, including the extent of access to inorganic fertilizers. Strategic and adaptive research to develop appropriate strategies and design systems incorporating OMM should include the following components:

- On-farm diagnostic research to describe current soil management practices, determine nutrient constraints and resource availability.
- Characterization and evaluation of available and potential sources of organic nutrients.
- Design of management systems appropriate to the given environment and farming system with particular reference to the biophysical and socio-economic limits and potentials of the target area.
- On-farm testing of the proposed management systems utilizing both farmer acceptance and sustainability assessment as well as production criteria.

This paper concentrates largely on the second of the above issues.

THE FARMING SYSTEM CONTEXT

The context for strategic research on the utilization of organic resources is established by the constraints experienced by and opportunities available to the farmer. On-farm diagnostic, design and evaluative components of OMM research have been reviewed recently by Swift and Izac, 1993; Swift *et al.* 1994a; Carter and van Oosterhout, 1994; Scoones and Toulmin, 1993.

PAPER 2.7

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FIGURE 1
Multiple effects of organic matter inputs (litter) on soil properties (from Swift and Woomer, 1993)

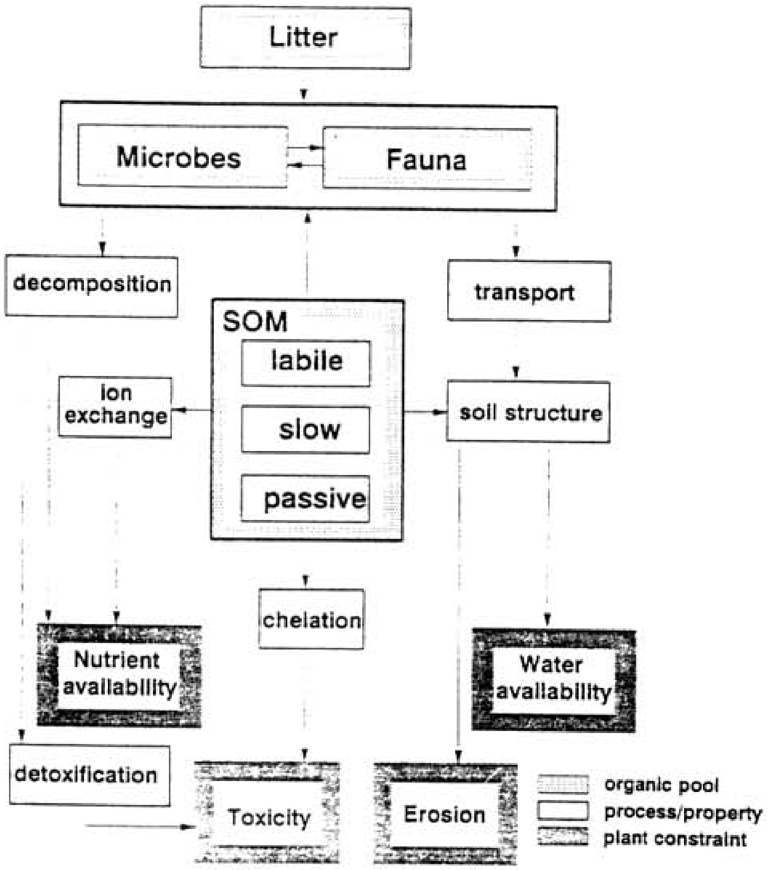


TABLE 1
Nitrogen fertilizer use profile for households in Mutoko Communal Area, Zimbabwe (modified from Campbell *et al.*, 1994)

	Mass uses (t/household/yr)	N input (kg/household/yr)	Frequency of use (% of household)
Purchased inorganic	n.a.	50.0	97
Manure	6.36	74.4	86
Leaf litter	0.42	4.5	36
Termite soil	3.67	5.1	23
Household waste	?	?	53
Compost	0.77	3.8	49
Collected stover	2.22	21.1	77

? = not known n.a. = not applicable

Farmers in Africa utilize a wide range of locally-derived organic and inorganic materials for soil management including crop residues, litter and prunings from trees, green-cut herbage, green manures, farmyard manures, household and industrial wastes and composts, soil from termite mounds and purchased inorganic fertilizers. In many cases a range of resources is available to the individual farmer (e.g. see Table 1) and the materials may be used singly or in combination. This provides for flexible and sophisticated strategies for soil management. Nonetheless, in the absence of purchased fertilizers, local materials may frequently be inadequate in quantity or diversity to supply all nutrient needs. Strategies for improved nutrient management require assessment of these needs and evaluation of the organic and inorganic resources required for supplementation.

EVALUATION OF ORGANIC RESOURCES FOR SOIL FERTILITY MANAGEMENT

Crop response to organic amendment

Crops respond differentially to the addition of different organic materials to soil. Interpretation of these results in terms of fertilizer effects is complicated by the differing nutrient contents of the materials and the variety of effects other than nutrient supply that they may have on crop and soil, such as the influence of the amendments on soil physical properties, micro-environmental changes, and interactions with pest and disease organisms. The residual effects of organic fertilizer use are also likely to be more long-lasting and more complex than those of inorganic fertilizers. Furthermore unequivocal nutrient balance experiments are more complex than with inorganic fertilizers because of the practical difficulties of labelling a wide enough range of organic materials. Thus despite the very large body of literature on the use of organic residues (e.g. Oschwald, 1978) there is very little information that enables rigorous evaluation of organic residues for their fertilizer value.

Evaluation of the fertilizer effects of an organic resource (e.g. for N) requires that the material be assessed both at an equal-N application and an equal-mass (or carbon) application, preferably in each case over a range of application rates. Even in these cases this does not remove differential effects of other components such as lignins and polyphenols (see below) or other nutrients, although the latter can be experimentally controlled by appropriate application of inorganic fertilizers.

An example from the Peruvian Amazon can be used to illustrate the types of effects that may be obtained in terms of crop responses to different organic materials. Three species of tree prunings, differing significantly in their chemical properties, were applied at different rates to four successive crops of upland rice on an ultisol in the humid forest zone of Peru (Palm, 1988). During the first crop mulching at neither low (3.3 t/ha) nor high (6.7 t/ha) levels produced a significant effect on rice yield but in subsequent crops mulched treatments had significantly greater yields than the unmulched control and the effect of increasing the mulch rate was also significant. Conversely, whilst there were significant differences in responses to the different materials during the first season, these effects disappeared in the later seasons. The N budgets for the lower mulch rate showed that the N-use efficiency for *Inga* was lower than for *Erythrina* or *Cajanus*, both of which were very similar to inorganic fertilizer (Table 2). The lack of difference in crop yields from the different mulch materials following the first crop may be the combined effect of release from newly applied mulches.

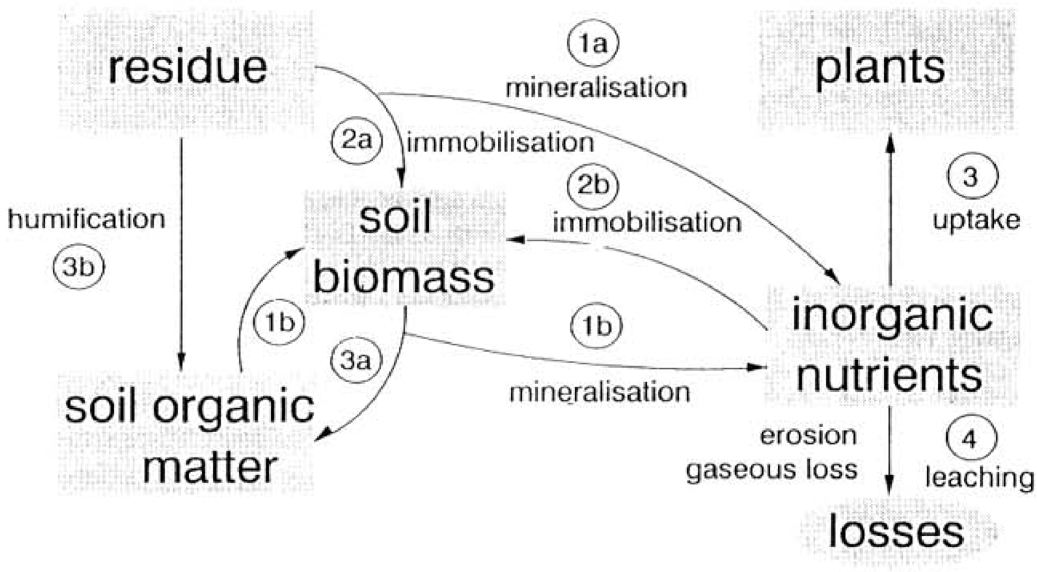
Regulation of nutrient flow from organic nutrients

Successful utilization of organic sources of nutrients relies on manipulating the biological processes of soil such as to optimize nutrient availability with respect to plant demand. A simplified model of the regulation of nutrient flux in agro-ecosystems is presented in Figure 2

TABLE 2
Nitrogen budgets and nitrogen utilization efficiencies for various types of mulch and N fertilization for four rice crops (Palm, 1988)

Treatment	N added	N removed (kg/ha)			N utilization efficiency (%)		N remaining in mulch-N (kg/ha)	Unaccounted for N	
		Grain	Straw	Total	Grain	Total		kg/ha	%
No mulch	0	46	45	91					
Mulch (3.3 t/ha)									
Inga	284	69	56	125	8.2	11.9	91	68	24
Cajanus	235	72	65	137	11.4	19.7	64	34	14
Erythrina	216	70	65	135	11.3	20.6	13	68	32
N-P-K fertilizer	400	77	105	182	8.0	23.0	n.a.	217	54

FIGURE 2
Model of nitrogen transformationpathways in the plant-organic matter-soil subsystems. Explanation in text (from Myers *et al.*, 1994)



(Myers *et al.*, 1994). This conceptual model depicts the flow of carbon and nutrients between organic residues, organic and inorganic pools in soil, and the plant. Pathways of loss are also included. Decomposition and mineralization of plant residue are mediated by both soil faunal and microbial populations. Some of the carbon and associated nutrients are mineralized immediately (pathway 1a) or are immobilized in the soil microbial pool (pathway 2a), later to be transformed into other soil organic pools via microbial byproducts (3a). Recalcitrant plant material also may enter the soil organic pools directly (3b). The carbon and nutrients held in the various soil organic matter pools are subsequently decomposed and assimilated by soil biomass resulting in additional mineralization (1b). The inorganic nutrients released by mineralization may be assimilated by soil biota, a process referred to as immobilization (pathway 2). Immobilization occurs simultaneously with mineralization and the rate at which nutrients are available for plant uptake depends on the net balance between mineralization (1a plus 1b) and immobilization (2). This is referred to as net mineralization. The inorganic nutrients may also be taken up by plants (pathway 3), lost by leaching or volatilization (pathway 4) or remain in the soil (Myers *et al.*, 1994). The size of the inorganic pool depends on the balance of the various processes that add to the pool (mineralization) and those that subtract (immobilization, plant uptake and losses).

The proportion of N transferred from the residue to the plant and the rate at which it occurs is determined by the balance between the rates of the various processes represented by these flux pathways. This balance is regulated by an hierarchy of factors. Environment, which includes climate and soil, is an overriding control which determines the rate of the transfer between pools. The rates will also vary depending on the quality of the decomposing substrate or the types of organisms present within the systems (Swift *et al.*, 1979). Soil management practices, such as tillage, can also significantly modify the regulatory hierarchy at all levels.

Predicting nutrient release patterns

Optimal development of integrated nutrient use systems will be achieved when it is possible to predict the outcome, in terms of nutrient cycling, of a given strategy for use and management of nutrient resources, both organic and inorganic. With regard to the use of organic sources of nutrient the required information includes the amount or proportion of nutrient that will be released by the processes of decomposition, the time course of this release and the partitioning of the nutrient after release (Figure 2). Considerable advances have been made in recent years in developing predictive models for some of these parameters. A review of this topic, including the empirical evidence on which current models are based is given by Myers *et al.* (1994).

Early studies of decomposition processes demonstrated the importance of N concentration and C/N ratio as a determinants of the N supplying capability of plant residues (Iritani and Arnold 1960; Swift *et al.*, 1979). More recent studies have revealed the significance of other modifying factors. For instance it has been demonstrated that in many instances the lignin concentration or the lignin:N ratio provides an effective index for N release patterns (Melillo *et al.*, 1982; Melillo and Aber 1984). Berg and McClaugherty (1987) suggested that N is not released from litter until decomposition of lignin commences. Feller (1979) proposed the ratio of neutral detergent fibre:cellular content (NDF/CC) as an index of potential N release and Gueye and Ganry (1978) applied the idea to results from a sandy soil in Senegal. Residues with high C/N and high NDF/CC contributed to N the organo-mineral fractions of the soil, whereas a material with similar C/N but low NDF/CC resulted in a release of mineral-N.

Polyphenols have also been implicated as regulators of N release in materials which, despite being nutrient-rich and low in lignin, are slow to release N (e.g. Vallis and Jones, (1973). It has been proposed that the polyphenols interact with a variety of forms of N to form stable polymers which are resistant to breakdown and thence delay N release (Martin and Haider 1980; Stevenson 1986).

These discoveries provide a basis for evaluating organic residues with respect to their potential behaviour as sources and suppliers of nutrients within cropping systems. For example Tian *et al.* (1992) investigated the patterns of decomposition and nutrient release of a range of crop residues and agroforestry inputs under field conditions in a humid tropical environment. They found that decomposition and N-release were strongly correlated with N, lignin and polyphenol concentrations (Tables 3 and 4). The patterns of release of P, Ca and Mg were

FIGURE 3

Relationships between nitrogen release and polyphenol: nitrogen ratio for eleven organic residues incubated in soil for eight weeks (from Palm and Sanchez, 1991)

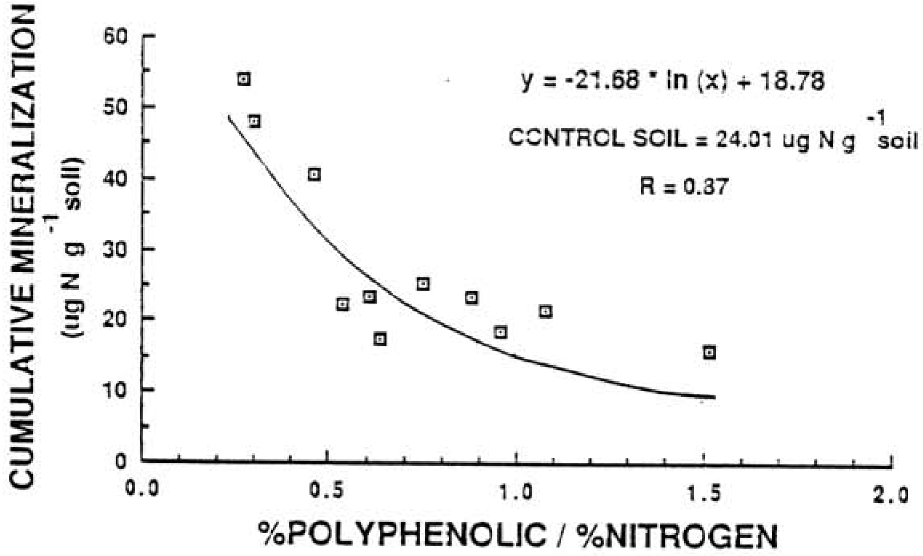


TABLE 3

Chemical composition (%) of agroforestry tree prunings and crop residues from Nigeria (Tian *et al.*, 1992)

Plant residues	Lignin	Cellulose	Hemicellulose	Polyphenols	C	N	C:N	P	K	Ca	Mg	SiO_2
Acioa	47.6	30.4	2.2	4.09	45.1	1.61	28.0	0.069	0.80	0.74	0.31	2.71
Gliricidia	11.6	19.4	12.2	1.62	47.3	3.60	13.1	0.129	2.74	1.63	0.45	0.59
Leucaena	13.4	21.1	13.5	5.02	45.5	3.55	12.8	0.092	2.79	1.59	0.40	0.53
Maize stover	6.8	36.7	35.6	0.56	42.6	1.00	42.6	0.133	2.06	0.42	0.29	2.22
Rice straw	5.2	40.1	22.9	0.55	35.5	0.84	42.3	0.053	2.34	0.58	0.31	11.35
LSD (0.05)				0.25	0.4	0.12	1.1	0.024	0.25	0.06	0.02	0.24

TABLE 4

Regression coefficient and partial correlation of effects of selected parameters on decomposition rate constant (k) from plant residues (Tian *et al.*, 1992)

	Regression coefficient	F	Probability >F	Partial correlation
C:N	-0.0035	13.30	0.004	-0.755
Lignin	-0.0023	8.90	0.014	-0.686
Polyphenols	-0.0188	4.82	0.053	-0.570
Mesh-size	0.0068	4.63	0.057	0.562
Constant	0.2736			

similar to that of N. On the basis of these observations they established the following predictive relationship for the rate of decomposition:

$$k = 0.2736 - 0.0035\ C:N - 0.0023\ \text{lignin} - 0.0188\ \text{polyphenols} + 0.0068\ \text{mesh-size}$$

where k is the decomposition rate constant per week.

In another example Palm and Sanchez (1991) determined the concentrations of N, lignin and polyphenolics in a variety of tropical legumes and investigated the relationship to rates of decomposition and nutrient release. Regression of N-release rate against the ratio of polyphenolic to N content could explain 76% of the variation in N release (Figure 3). Similar results indicating the importance of polyphenol:N in controlling N mineralization from legumes have been obtained by Oglesby and Fownes (1992) but Fox *et al.* (1990) found that the best predictor of N mineralization from shoots of a range of tropical legumes was a ratio combining three factors (lignin + polyphenol)/N.

Whilst there are some differences in detail in these examples (which may be due to differences in analytical methods for polyphenols) they serve to illustrate that the methodology is available to assess predictively the nutrient release patterns of organic residues on the basis of knowledge of their chemical composition. This information greatly facilitates the potential for design of nutrient management strategies. This information can also be incorporated into simulation models to predict longer term trends in soil organic matter dynamics and other aspects of soil fertility (Parton *et al.*, 1989; Woomer, 1993).

Partitioning of nutrients

Optimalization of the use of organic residues as fertilizers is dependent on predicting the efficiency of transfer of nutrients from residue to plant. Measurement of crop response to organic amendment does not alone constitute evidence of a fertilization effect.

TABLE 5
Partitioning of N added in labelled plant residues to the subsequent crop and to soil organic matter

Authors	Crop (%)	Organic matter (%)
Ladd *et al.*, 1981	11-17	72-78
Janzen *et al.*, 1990	14	21-40
Ng Kee Kwong *et al.*, 1987	11-14	73-84

The strongest evidence for nutrient transfer is obtained in studies using isotopically labelled material (Table 5). During decomposition there is partitioning of N firstly between mineral-N and microbial-N (pathways 1a and 2a; Figure 2), then with turnover of microbial-N, into mineral-N, humic-N (1a and 3a) and again into microbial-N. The N use efficiency of plant residues by a first crop is in the order of 15% for legume residues and 5% for cereal straw residues, but there is much variation. This compares with up to 60% of N applied in inorganic fertilizer being utilized by the first crop. Some residues release less N than expected, for example *Desmodium intortum* (Vallis and Jones 1973) and *Leucaena leucocephala* (Xu 1991; Sandhu *et al.*, 1990; Mulongoy and van der Meersch 1988; Read *et al.*, 1985). In many cases however there is a consistent pattern to the partitioning of N between the mineral N and humic N pools (Table 5). The high proportion of transfer to SOM suggests that in terms of nutrient supply residual effects are likely to be more important than those in immediate seasons. This is the consistent finding from long-term experiments (Swift *et al.*, 1994b).

CONCLUSIONS: DESIGN OF ORGANIC MATTER MANAGEMENT STRATEGIES AS A COMPONENT OF INTEGRATED NUTRIENT MANAGEMENT

Strategies for organic matter management should be designed in relation to the environmental determinants which regulate the biological processes of soil and build on the current resource management practices of the farmers. The degree of flexibility varies greatly but many current practices of soil management in small-scale farming systems offer a diverse and sophisticated base on which to build. Table 1 showed the inputs used by farmers practising mixed livestock-arable farming in North Eastern Zimbabwe. The soil management practice is characterized by use of multiple resources and heterogeneous distribution of the inputs to different micro-environments on the farm (Campbell *et al.* 1994). With such a range of resources and environments there exists the opportunity to exploit a range of strategies for soil management based on manipulation of the biological processes regulating soil fertility (Table 6).

TABLE 6
Soil management practices which influence biological activities and nutrient cycles

a.	Manipulation of the physico-chemical environment by tillage, irrigation, mulching, fertilization and liming changes the soil environment in such a way as to influence the composition of the soil community and the rate of biological processes.
b.	Manipulation of both the quantity and quality of the inputs to soil food chains through varying the amount and diversity of crop residues, and other organic and inorganic materials added with them, directly influences the rate of biological processes.
c.	Manipulation of the temporal and spatial distribution of organic inputs influences the pattern of biological processes in time and space.
d.	Selection of crops and/or soil micro-environments for differential application of inputs and management practices influences the efficiency of nutrient return.

Manure is a key component in this livestock-based system (Table 1) but under changing circumstances in the agricultural sector in Zimbabwe the availability of this resource and its quality as a fertilizer are both declining (Murwira *et al.* 1994). This presents a challenge to the scientist to design management strategies that increase the nutrient availability and use-efficiency without destroying the basic structure and potential sustainability of the current system. This strategy thus not only requires policy elements in relation to access to purchased inputs but also the means of introducing additional or alternative organic resources through practices such as agroforestry, green mulching or boundary planting. Other systems in different environments have different options and priorities but the research needs for improved organic matter management remain the same.

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Technological options for controlling soil organic matter losses in tropical rainfed cropping systems

Since the beginning of agriculture, it has been recognized that dark soils, principally found under forest, in river valleys and in broad grass plains, are usually (but not always) productive soils. It was also realized that soil colour and soil productivity are associated with soil organic matter (SOM) derived from plant residues and animal excreta.

Both in temperate regions and in the tropics, the control of SOM loss under continuous cropping has been one of the major aims of traditional agriculture, together with the control of soil erosion. The use of organic inputs was reported in the Near East as far back as 2000 BC, and later in settled agriculture in China, Japan, India, Mexico, Peru and the Greek and Roman Empires (Allison, 1973). It should be noted that terracing has been extensively developed in the same areas (Simmons, 1987).

However in the tropics, shifting cultivation has until now been the more common farming system, *in which annual or short-term perennial crops are planted for a few years on forest clearings or grass savannah burnings followed by fallows for up to three or four decades.* Conditions which limit yields such as weeds, pest outbreaks, soil fertility and SOM losses are overcome during the long fallow period following the few years of cultivation.

With the dramatic growth in population experienced in tropical countries, shifting cultivation is no longer a sustainable option. Hence, the maintenance of soil productivity to support the future increase in food production is a challenging and urgent matter in the tropics, as it is expected that 75% of this increase (Crosson and Anderson, 1992) will have to come from the 730 million hectares of tropical land already cultivated (WRI, 1992).

This paper focuses on issues related to processes and related technologies controlling SOM losses in tropical rainfed agriculture and annual cropping systems for which SOM losses are both intense and most detrimental to soil productivity.

The control of SOM balance, rather than the mere control of SOM losses, is critical to meet FAO's goal of promoting Integrated Plant Nutrient Systems (IPNS) in the broader perspective of sustainable land management in the tropics. Appropriate technological options are generally known and available; however, the main issue is the implementation of technologies which must be tailored to local physical and socio-economic conditions through a participatory and multidisciplinary approach.

PAPER 2.8

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The **first section** analyses briefly why the control of SOM balance is of primary importance in tropical agriculture, although not fully evident in modern agriculture in temperate regions. The **second section** investigates, through selected examples, the specific objectives and the temporal and spatial dimensions of known technologies to achieve an efficient control of the SOM balance in sustainable tropical cropping systems. The **third section** summarizes the significance and application of these findings for FAO to foster the implementation of technological options coherent with the IPNS and good land husbandry.

SOIL ORGANIC MATTER BALANCE AND TROPICAL SOIL PRODUCTIVITY

In the context of this paper it is not possible to address all the issues related to the complex relationships between the SOM balance and the productivity of tropical soils.

While SOM content is usually regarded as a key factor in the maintenance of soil productivity, it is certainly not the only one, even though environmental concern gives now more attention to C sequestration in soils. Then the importance given to the application of organic inputs in tropical agriculture is often a matter of contention. It should be carefully analysed as crops basically need only sunlight, air, water and inorganic salts to give maximum yields.

SOM content and soil productivity

SOM has for a very long time been associated with fertile soil. Howard in his book "An Agricultural Testament" (1943) wrote: "*In a fertile soil the soil and the plant come into gear in two ways simultaneously. In establishing and maintaining these contacts humus is essential. It is, therefore, a key material in the life cycle. Without this substance the wheel of life cannot function effectively*".

A relationship between SOM and soil fertility/soil productivity does exist but is certainly not restrictive. Other key soil factors can severely constrain soil productivity, such as acidity, nutrient deficiencies or salinity, in addition to socio-economic factors. Soils with high SOM content can even have a low productivity induced by strong acidity and poor nutrient availability, as in the cool tropical environment of the African heights (e.g. NW Rwanda).

However, the favourable roles of SOM are mostly recognized and well documented under low-input land use systems (Nye and Greenland, 1960; Charreau and Nicou, 1971; Lal, 1987; Young, 1989) as well as under medium and high-input systems (Johnston, 1986). A recent IITA publication related to "Sustainable Food Production in Sub-Saharan Africa" (1992) has a full chapter entitled "The Centrality of Soil Organic Matter" which bears on the multiple favourable roles of SOM briefly listed hereafter: improvement and stabilization of soil structure, decrease of soil compaction, increase of soil water permeability and often of the water holding capacity, increase of nutrient storage capacity including trace elements, better buffer power and phosphorus availability in case of high P fixing soils, enhancement of biological nitrogen fixation (BNF), better soil and land pollution control vis-à-vis heavy metals (Cd, etc.) and pesticides, and more generally enhancement of favourable biological activity resulting in a better 'synchrony' between plant requirements and water and soil nutrient availability. SOM plays a central role both as a sink and source for nutrient/chemicals and often for water.

TABLE 1

Effect of manure on nutrient uptake by a groundnut crop in mid-growth (Thilmakha, Senegal) (Cissé, 1986)

Treatment	Soil solution content (mg/l)			Uptake (kg/ha/day)			Root uptake (mgg root/day)		
	N	P	K	N	P	K	N	P	K
Fertilizer	13	-	13	0.85	0.09	0.50	3.6	0.4	2.1
Fertilizer + manure	36	-	22	3.80	0.50	1.30	14.1	1.8	4.8

TABLE 2

Potential global biological carbon sequestration and conservation above and below ground, to reduce atmospheric CO_2 (Source: EPA, 1991)

		US	Boreal	Tropical	Temperate
		Gt C/yr			
Sequestration	• Forestation	0.10	0.1	1.9	1.6
	• Agroforestry	0.05	---	2.1	0.1
	• Revegetation	0.05	0.4	0.9	0.2
	• Silviculture	0.03	0.1	0.2	0.1
Conservation	• Reduce deforestation	---	0.1	1.5	---
	• Halt desertification	---	---	0.2	0.2
	• Fire management	---	0.2	---	0.2
Totals		0.23	0.9	6.8	2.4

A range of terrestrial biosphere management options which conserve or sequester carbon are available for utilization in the USA and biomass worldwide. Based on current estimates, application of forest management and agroforestry systems on a global scale could potentially sequester and/or conserve up to 10.1 Gt C annually. Many of these options have value added benefits beyond the reduction of greenhouse gases.

The net result is often, but not necessarily, a better soil productivity over time which can be ascribed to a more efficient use of the available nutrient and water resources, particularly under low-input systems in semi-arid tropical environments (Table 1) as well as in the humid tropics (Sanchez *et al.*, 1990). **Finally, SOM management is crucial to IPNS.**

It is now also acknowledged that the importance of SOM management goes much beyond sustainable agricultural land management, as soils are a major source and sink for C with a high potential impact on the global environment. Soils contain approximately twice as much carbon (1400 Gigatons) as either the terrestrial vegetation or the atmosphere (700 Gigatons). The highest potential for biological C sequestration and conservation is to be found in the tropics through sustainable agriculture practices (Table 2).

Causes of change in SOM content

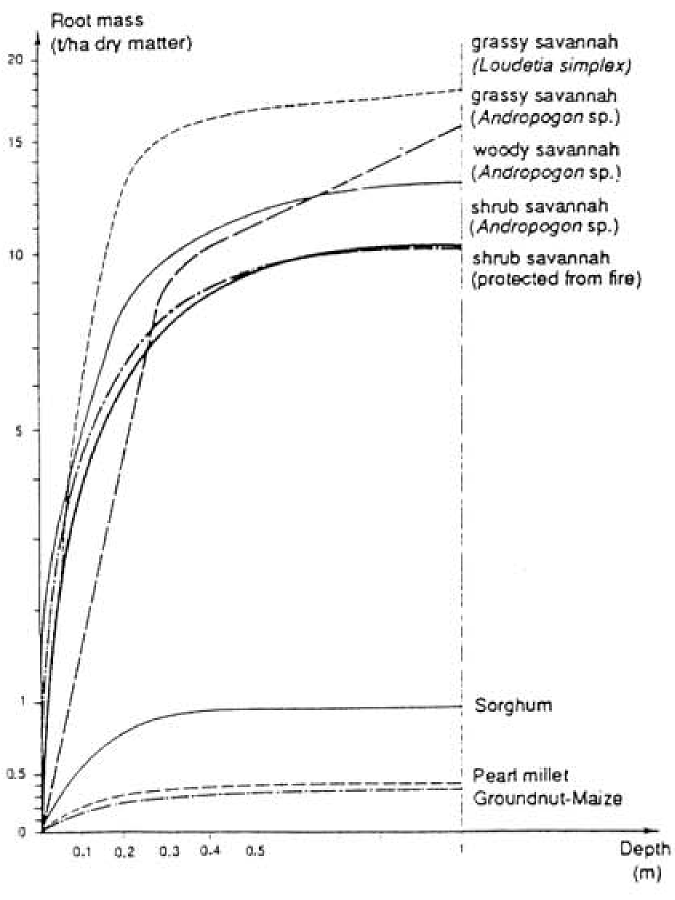
In general terms SOM content is a function of additions and of decomposition rates. **No differences in organic matter content, or in the quality** of the organic constituents, have been found **between soils of the tropics and soils of the temperate regions** in uncultivated, forested ecosystems, or between Oxisols and Mollisols (Coleman *et al.*, 1989).

Many processes operating at site-specific rates affect actual input and decomposition rates, leading to a wide range of equilibrium SOM contents in the tropics as in the temperate regions (Anderson and Swift, 1983). What then is the difference? **The major difference is not related to SOM content but to the more rapid cycling, 'turnover', of organic matter in tropical cultivated soils.**

Addition and decomposition rates

On average, the tropics are 15°C warmer than temperate regions. In addition they have no cold winter which favours the synthesis of stable-humus. This higher temperature results in a several-fold increase in chemical and biochemical reactions occurring in soils. Hence, with land clearing and continuous cropping, the SOM content declines much more rapidly **under tropical conditions** than under temperate conditions, because **the decomposition rate of SOM is more intense, while the primary rate of vegetative production is not increased in proportion** and may even decrease, particularly in terms of root biomass production (Figure 1).

FIGURE 1
Root mass distribution under natural cover compared to crops (Chopard, 1980; Lamotte and Bourlière, 1978) (Source: Pieri, 1992)



Of course SOM is not a single, homogeneous entity and the decay rates change according to the type of organic fractions: faster for non-humified plant residues (half-life approximately less than 6 months), medium for labile-humus (half-life less than 3 years), slower for stable-humus (half-life exceeding normally 50 years) (Jenkinson and Ayanaba, 1977).

While recognizing the diversity of organic fractions in soils it is important to assess the rates of SOM change over time. On average, for most tropical soils, the **annual rates of decomposition of SOM, through microbial oxidation, fall commonly in the range of 3 to 4%** (Table 3). It is, of course, the more labile fraction of SOM which is decomposed and which is thus responsible for this loss.

Even though soil temperature, soil moisture, texture and clay mineralogy are recognized as the main determinants of SOM content in the tropics (Coleman *et al.*, 1989), decay rates are mostly affected by **soil and land management**. In the humid tropics, Sanchez (1976) reports annual SOM decomposition rates ranging from less than 1% to more than 10% according to crop and soil management. Similarly, in a recent review of the results of long-term experiments in the semi-arid West African savannah region, Pieri (1989) found that annual decomposition rates of organic matter in sandy soils fall in the same range, between 1 and 10%. An empirical relation which draws on these results is proposed to evaluate k_s, the annual rate of SOM decay under improved technology in relation to the k_0, the basic rate of decay under manual conditions. This relationship should be brought to the attention of project managers and policy-makers on account of the long-term impact of the specific influence of soil intensification technologies, such as fertilizer application, ploughing etc. (Table 4).

Most of these data relate to SOM changes in the top layer (20 cm) of the soil profiles. However, in contrast with traditional shifting cultivation, with long periods of fallow (Greenland, 1970), settled agriculture increases the rate of SOM loss, not only at the surface but **also in the deeper layers of the soil profile** (see Figure 2).

TABLE 3

Estimates of the litter-to-humus conversion loss and the humus decomposition constant. Data are not fully comparable, owing to different assumptions made. Kf = under vegetation (fallow), Kc = under cultivation, Ka, Kb = different organic matter fractions, Kn = for release of nitrogen, r = see text. (Source: Young, 1989)

Country, environment	Litter-to-humus conversion loss in 1 yr (fraction)	Humus decomposition constant (fraction)
West Africa		
forest	above ground:	Kf = 0.03
	0.75 - 0.9	Kc = 0.033
savannah	roots:	Kf = 0.008 - 0.009
	0.5 - 0.8	Kc = 0.045
Senegal		
savannah	0.5 - 0.9	Kf = 0.04 - 0.07
woodland		Kc = 0.02 - 0.05
forest		Kf = 0.44, Kc = 0.06
savannah		K = 0.02 - 0.09
Nigeria		
savannah		Kc = 0.04 - 0.05
moist sub-humid		K = 0.07
Costa Rica	0.65	K = 0.13
UK		Ka = 0.014
temperate		Kb = 0.00035
Costa Rica	0.64 - 0.77	r = 0.12 - 0.23
Queensland		Ka = 0.153 - 0.371
		Kb = 0.022 - 0.0036
South Australia	0.7	
Thailand		K = 0.077 - 0.088
UK		Kn = 0.028
temperate		
USA		Kn = 0.024 - 0.063
temperate		
Zaire		Kn = 0.330
Assam, India		Kn = 0.099
Puerto Rico		Kn = 0.224

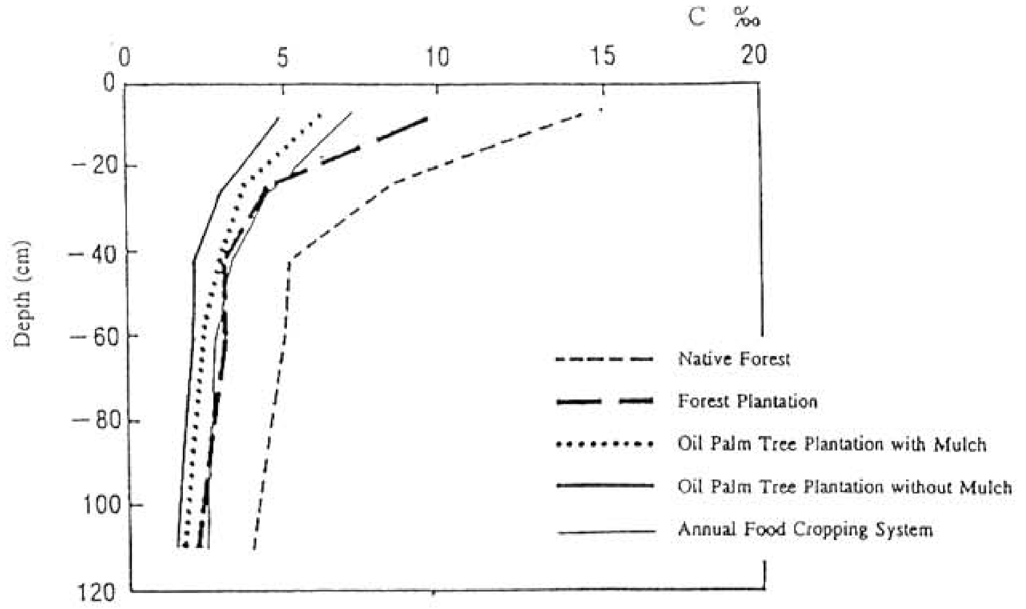
Soil erosion, burning of vegetation

The impact of water runoff and soil erosion on SOM matter is well documented (Sanchez, 1976; Roose 1977; Lal 1987; von Uexkull, 1982). Table 5 illustrates the effect of erosion in China under natural vegetation. Similar data suggest that sheet erosion, which is more likely to occur under natural vegetation and which induces a selective and significant decline in SOM content of the top soil, might well be more pernicious in the long term because it is less visible than dramatic forms of erosion such as deep gullies.

TABLE 4
Values of multipliers used for calculating k_s from k_0. ($k_s = k_0 \cdot \alpha \cdot \beta \cdot \gamma \cdot \delta$)

Soil Type	Basic rate of SOM loss k_0 (%)	Effect of ploughing α	Effect of incorp. of straw β	Effect of rotation γ	Effect of complete fertilizer δ
Very sandy	4	1 to 1.6	1.4	0.9	0.8
Loamy sand	2	1 to 1.2	1.2	0.9	0.8

FIGURE 2
Change in soil carbon content after a fifteen-year period under different farming systems, Akpanadoure, Benin (Source: IRHO, 1992)



Regular fires are a universal event in tropical savannah ecosystems. Fires reduce standing biomass and litter, kill seeds, seedlings and fauna. Fires also promote a better growth of natural grasses during the next rainy season, and ultimately the carbon status and productivity of savannahs is determined by the frequency, timing and intensity of burning (MAB, 1993). It should be added that seasonal wind such as the Harmattan in West Africa and transportation of ashes and aerial dust over long distance (several hundred kilometres) is equally an important cause of C loss in these periodically burnt ecosystems (Monnier, 1990).

Deforestation has a clear impact on C emission in the atmosphere (Table 6), and on SOM loss. This loss is currently increased not only by the decrease in organic additions and enhanced oxidation but also by the impact of soil erosion triggered by deforestation, particularly when the felling of the trees is achieved under unmastered mechanized conditions (von Uexkull, 1982).

SOM balance

In tropical agriculture it can be broadly stated that, under the current circumstances, **the SOM level improves or is maintained under the natural vegetation, while it declines under arable agriculture.** Figure 3 illustrates the case of such a negative balance in a lowland humid tropical zone (Young, 1989). In practical terms this means that improved farming and land systems must be implemented to replenish SOM from one crop cycle to the next.

TABLE 5
Effect of erosion on organic matter content of tropical and subtropical soils under natural vegetation in China (Source: Yu, 1989)

Soil	Status	OM (%)
Latosols	Non-eroded	4.04
	Eroded	1.73
Red earths	Non-eroded	4.39
	Eroded	1.56
Yellow earths	Non-eroded	6.69

TABLE 6
Sequestered carbon lost from global deforestation. Tons of sequestered carbon lost per year (EPA, 1991).

Nation	Deforest 10^3 ha	I/C per ha	Tons of C 10^6
Brazil	9050	260	1177
India	1500	214	161
Indonesia	920	214	98
Colombia	890	169	75
Myanmar	677	214	72
Mexico	615	169	52
Cote d'Ivoire	510	260	66
Sudan	504	260	66
Nigeria	400	260	52
Thailand	397	214	42
Zaire	370	260	48
Ecuador	340	169	29
Peru	270	169	23
Malaysia	255	313	40
Venezuela	245	169	21
Paraguay	212	169	18
Cameroon	190	199	19
Viet Nam	173	214	19
Total	17 518		2078

Based on a set of hypotheses on the dynamics of organic matter and on the impact of the causes of SOM change over time, Young (1989) evaluated indicative plant biomass requirements for the maintenance of the SOM balance (Table 7), and speculated that agroforestry opens exciting prospects to lead to a steady state of SOM in the tropics.

To conclude this section it emerges that, in the perspective of developing IPNS and sustainable land management in the tropics, it is of vital importance **to promote technologies which are productive in terms of agricultural outputs and at the same time lead to a favourable SOM balance.**

FIGURE 3

Carbon cycle under a cereal crop, lowland humid zone, crop yield 3000 kg/ha. Values are kg C/ha and kg C/ha/yr. Shaded areas show net losses of soil carbon (Source: Young, 1989)

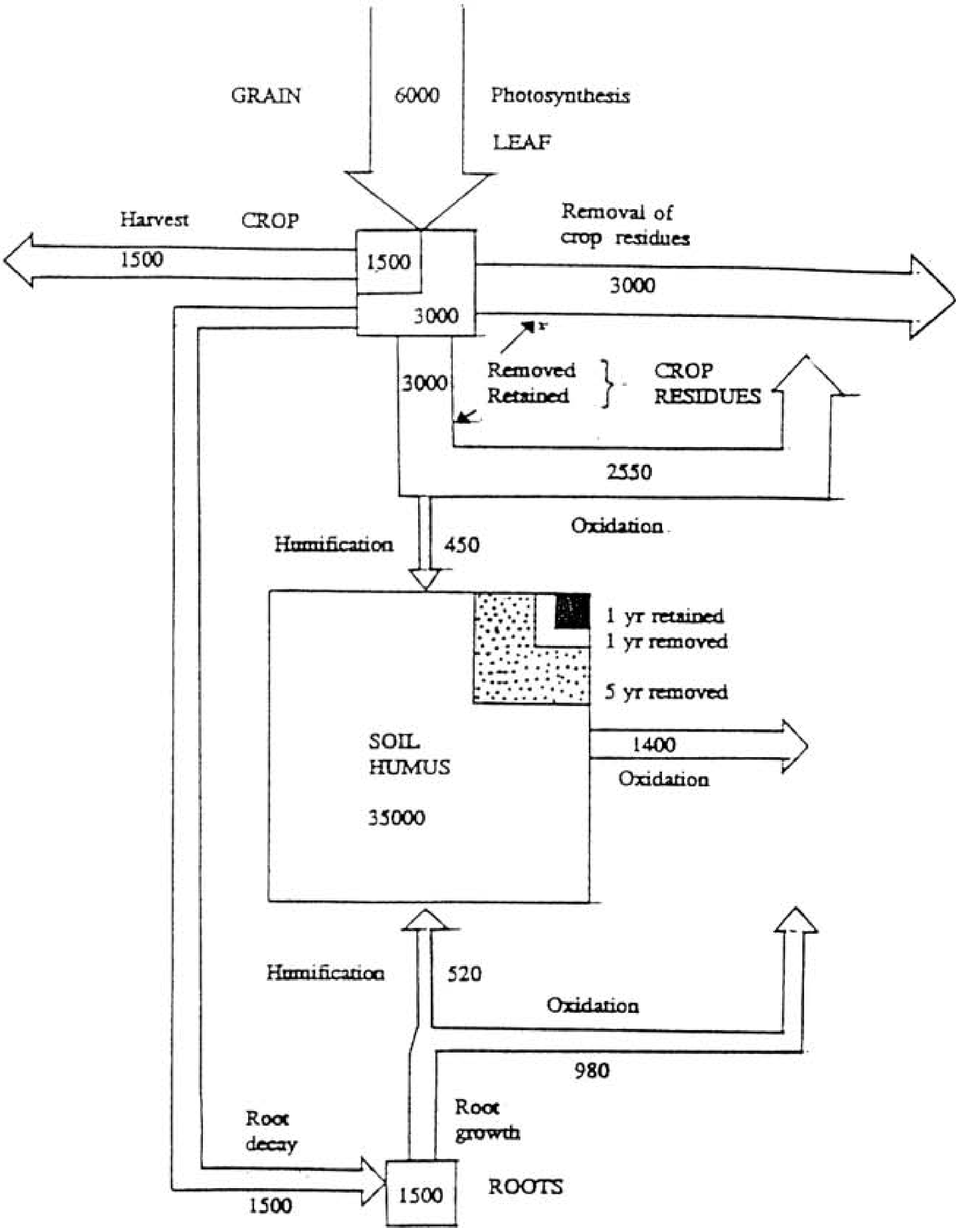


TABLE 7
Indicative plant biomass requirements for maintenance of soil organic matter (Young, 1989)

Climatic zone	Initial topsoil carbon (kgC/ha)	Topsoil carbon (%)	Oxidation loss (kgC/ha/yr)	Erosion loss (kgC/ha/yr)	Required addition to soil humus kgC/ha/yr	Required plant residues added to soil (kg DM/ha/yr)	
						above ground	roots
Humid	30 000	2.0	1200	400	1600	8400	5800
Sub-humid	15 000	1.0	600	200	800	4200	2900
Semi-arid	7 500	0.5	300	100	400	2100	1400

TECHNOLOGICAL OPTIONS CONTROLLING THE SOM BALANCE

Improvement and maintenance of SOM is one of the most challenging aims to be reached by technologies adapted to the tropical environment. These technologies should follow some specific objectives, based on a sound agro-ecological approach. They also have to be designed within a comprehensive time and space framework.

Major objectives and approaches

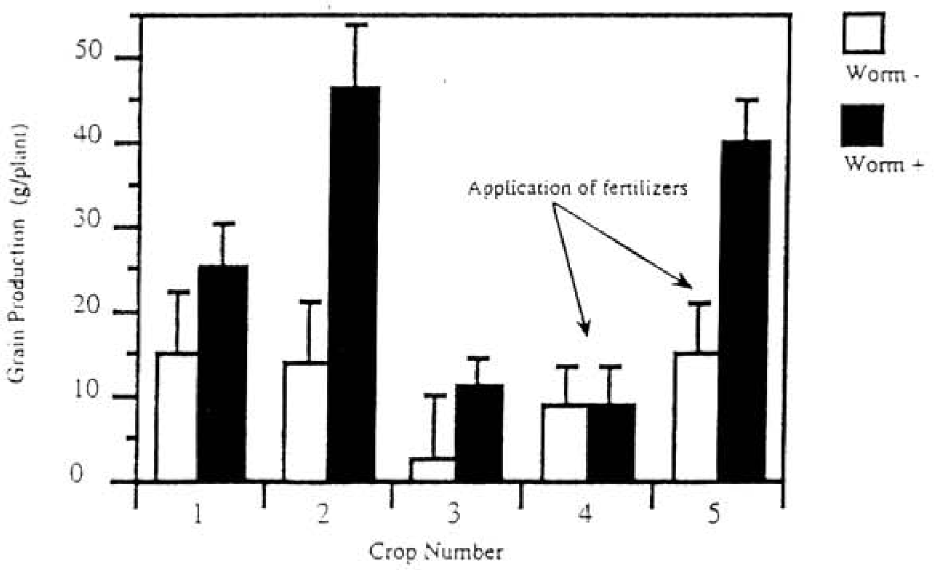
Improving SOM content and maintaining the SOM balance in farming lands can only be achieved by:

- **increasing biomass production per unit cropped area**: by elimination of major soil inherent constraints e.g. water harvesting techniques and nutrient application to overcome major N, P, S deficiencies in semi-arid tropics, soil acidity control, eradication of soil compacted layers and control of P, K, Zn, etc. deficiencies in humid tropics;
- **increasing biomass return to cropped area**: mixed-farming, crop rotations, BNF species, improved species and crop/tree associations which favour a quick establishment of dense and deep root systems;
- **decreasing SOM loss per unit cropped area**: decreasing soil erosion (particularly sheet erosion), decreasing SOM decomposition rates and enhancing soil humus accumulation through soil temperature control (decrease) and soil fauna stimulation.

Basically, these three objectives can be fulfilled through two different but complementary approaches.

For years the scientific community has focused on approaches and related technologies which deem to overcome major soil constraints through irrigation, drainage, tillage and application of fertilizers and amendments in order to meet the plants' requirements and to develop intensive agricultural systems. This approach, together with the development of high yielding varieties, is responsible to a very large extent for the very significant increase in food production in developed and developing countries. While this approach is commendable for fertile land, it is less clear how to implement these technologies in more fragile environments which have been put under cultivation by poor farmers for the last decades.

FIGURE 4
Effects of earthworm inoculation on grain production in a continuous maize crop at Yurimaguas
(Source: Lavelle *et al.*, 1992)



Agro-ecology is then the starting point of a second approach. Agro-ecology is an applied science which "tries to understand how physical conditions, soils, water, nutrients, pests, biodiversity, crops, livestock and people act as interrelated components of agro-ecosystems, emphasizing the structure and function of the system as a whole" (NRC, 1993). Recently, in response to UNCED's Agenda 21, a task force of the CGIAR also recommends such an approach, in favour of "a new soil paradigm, which relies more on biological mechanisms by adapting germplasm to adverse soil conditions and water stress, maximizes nutrient cycling to minimize external inputs and increases the efficiency of their use". Since 1990 the "Tropical Soil Biology and Fertility" programme has published several articles and reports related to this approach and its applications (TSBF, 1993).

This second agro-ecological approach is clearly closer to the concept of IPNS.

However, it would be unwise to regard the two approaches as mutually exclusive because:

- local needs, ecological circumstances, economic opportunities, social and cultural factors as well as the status of land, etc., will determine which practices are most relevant; for instance, from an agro-ecological perspective, the ploughing under of crop residues may be recommended to maintain SOM content in humid tropical farming environments, but proves to have a long-term adverse effect on the SOM balance of coarse textured soils of West Africa, because of the over-stimulation of heterotrophic soil micro-organisms which tend to deplete the reserve of stable-humus (Pieri, 1992);
- basic scientific concepts are the same for both approaches; for instance in any agricultural or forestry system, nutrient loss through harvesting and unavoidable leaching **must be**

balanced with nutrient inputs in the form of mineral fertilizer, manures or biological nitrogen fixation; data prove that soil fauna management, as experienced by earthworm inoculation (Yurimaguas, Peru), does not change this basic rule (Figure 4, Lavelle *et al.*, 1992).

List of specific practices associated with sustainable agriculture and eventually SOM balance control

In the context of this paper, it has not been feasible to address all the possible technological options associated with the control of SOM balance in the perspective of sustainable management of tropical rainfed cropping systems.

The wide array of specific practices already available includes (NRC, 1993):

- low-impact land clearing techniques;
- mulches, cover crops and understory crops;
- vegetative barriers and non-structural soil erosion control methods;
- fertilizers and other soil amendments;
- no – and minimum – tillage techniques;
- increased use of legumes as food crops, as cover crops and in pastures;
- improved fallow/pasture management techniques;
- use of selected and alternative crops, grasses, shrubs and trees, especially those tolerant to stress environment (e.g. high aluminum, low available P, etc.) and those that take fuller advantage of available resources both above ground (sunlight, nutrient reserves and biotic interactions) for instance through mixed cropping/intercropping practices and below ground for instance through the use of legumes and deep-rooted crops;
- a variety of agroforestry systems that mix crops, multi-purpose trees and livestock;
- etc.

Besides the necessary adaptation of these practices to local circumstances, it is important to reflect on the spatial and time dimensions of the selected technologies to be implemented.

Spatial dimension

Watershed scale

From an agro-ecological point of view, the optimum renewable natural resources use requires a **diversity of systems and system components which match with the inherent diversity of the physical and human environments**. In any rural area, say several thousand hectares, where an agricultural development project is implemented, land zoning is required to adapt technological options to the current agro-ecological diversity. There is nowadays a growing interest in combining the existing scientific knowledge of tropical agro-ecosystems with empirical experience of farmers, herders and foresters. For example, farming activities in Africa are organized partly in relation to soil qualities at the toposequence scale (Angé, 1991) and partly at farm and village scale within the physical boundaries of one or more watersheds.

While acknowledging that the biological processes and physical and chemical factors regulating plant production are integrated at the cropping system scale, it is also essential to integrate some socio-economic conditions such as land tenure and access to resources, for farmers and herders, for men and women, which will eventually lead to proposing of a set of technological options able to promote a sustainable land use management. In West Africa this **"catchment-village"** dimension (Izac and Swift, 1993) or **"approche gestion de terroir"** is getting greater recognition and inspires new projects of rural development prepared and funded by donor agencies. The merging of agronomic and socio-economic perspectives at the earliest stage of any project (Byerlee *et al.*, 1991) might well be a vital step in the implementation of IPNS and sustainable land management.

Field scale

At field level, the key to successful soil management is to maintain a continuous ground cover at all times, at least during the cropping cycle. There is growing evidence that this vegetative protection can be satisfactorily achieved through **conservation tillage** and particularly **direct drilling** on permanent mulch cover in humid tropical mild conditions (Crovetto, 1992; Derpsch *et al.*, 1991) and warm (Lal, 1989; Sheng and Meiman, 1991; Séguy *et al.*, 1991). The direct drilling technology appears to be more and more mastered, particularly in Latin America where suitable **mulch covers** adapted to a wide range of tropical environments have been identified and tested at farm level. A new promising development is the use of some native weeds (Ramakrishnan, 1992). Appropriate **equipment** for sowing and fertilizer application through a thick layer of mulch cover is now available, particularly in Brazil where hand tools, oxen drawn and motorized implements are commercially marketed. Mechanized Brazilian farms are experimenting with new equipment ("Vibrasol" and/or chisel plough) to address the issue of soil compaction which may occur principally on sandy soils (more than 70% of sand in the top layer). Finally, new formulae of **pesticides**, with high efficiency for weed and pest control, are currently being tested at low rates of application.

More and more scientists (Kang *et al.*, 1984; El Swaify *et al.*, 1987; Lal, 1987; Sanchez *et al.*, 1990; Crovetto, 1992) have also come to the conclusion that direct planting methods on mulch cover are cost effective in containing soil degradation, maintaining high standards of soil fertility and sustaining soil productivity in the humid tropics. However, much of this work has not gone beyond scientific investigation and pre-development. It must be concluded that more experience is required and that the implementation and assessment of such methods, both in commercial and, even more so, in present smallholder agriculture, should be encouraged.

Time dimension

The **transition** from current practices to more sustainable agricultural and land-use systems is not without difficulty, particularly in the early stages when investment in time, labour and money are required. From a technological perspective it means that specific and discrete technological components must be clearly identified to allow farmers to move from their current cropping system to a better one.

Table 8 illustrates the case of the adoption of a direct drilling system in the Brazilian cerrado zone which, for its successful implementation, requires an initial deep ploughing phase to break a compacted soil layer which is a major constraint to direct drilling practices.

During this transition phase the establishment of **soil conservation systems** is of seminal importance and, particularly, vegetative systems which have proved to be cheaper and more effective than conventional systems of earth bunds or terraces. The system of hedges of vetiver grass (*Vetiver zizanioides*) is certainly the most popular on steep slopes and is well documented (World Bank, 1993). In China vetiver is being grown as hedges on 60% slopes to protect tea

TABLE 8

Effect of conventional and direct planting (no tillage) practices in the presence of a cover crop (*Calopogonium mucunoides*) on the yields of crops in rotation, Fazenda Progresso, Mato Grosso, 1987-90 (Source: Séguy *et al.*, 1991)

1986-87	1987		1987-88		1988-89		1989-90	
	Crop and soil management		Crops	Yield (kg/ha)	Crops	Yield (kg/ha)	Crops	Yield (kg/ha)
Sowing of a mixture of rice and *C. mucunoides*. Rice yield = 3225 kg/ha	Deep ploughing	Fertilized with NPK[1] at seeding	Soybean	1215	Maize	4700	Soybean	1755[3]
			Maize + *Calopogonium*	4030			Maize	2678
	Deep ploughing	Thermophosphate Yoorin Bz 1500 kg/ha[2]	Soybean	1440	Maize	6500	Soybean	900[3]
			Maize + *Calopogonium*	4226			Maize	3068
Soil cover at the end of the dry season (straws or rice + *C. mucunoides*) = 12.5 t/ha	Direct planting	Fertilized with NPK[1] at seeding	Soybean	2040	Maize	5200	Soybean	2460 5200
			Maize	4360			Maize	
There is natural dissemination of *C. mucunoides* the following years	Direct planting	Thermophosphate Yoorin Bz 1500 kg/ha[2]	Soybean	2486	Maize	6400	Soybean	2947
			Maize	4940			Maize	5830

[1] NPK fertilizer placed at seeding
. soybean: 350 kg/ha 0-25-25
. maize: 350 kg/ha 5-30-15 + 100 kg/ha urea

[2] Fertilizer thermophosphate
. 1500 kg/ha of Yoorin Bz applied in 1987 for three years complemented with N and K to achieve same level as [1]

[3] Plots dominated partly or totally by *Calopogonium* sp.

and citrus crops on acid (pH 4.1) red soils. Other systems, including 'cordons pierreux' are equally effective, particularly to protect iron-crusted shallow soils against run-off and erosion in semi-arid West Africa (Burkina Faso, Senegal).

In conclusion, one may keep in mind that the agro-ecological approach and the related technologies, briefly described here, will eventually '**mimic nature**' in its surprising ability of making the best use of relief, orientation, soil types, moisture nutrient reserves and biotic interactions resulting in sustainable and resilient natural ecosystems.

CONCLUSIONS

What can be learned from a more focused attention on the question of controlling SOM losses in tropical cropping systems in relation to the development of IPNS? The scientific community provides a wealth of information which deems to prove that SOM is a corner-stone for the building of any sustainable annual cropping systems in rainfed tropical agriculture. The difficulty lies in the maintenance of an appropriate SOM balance because the decay rate of SOM is very rapid in cultivated soils. This decay rate is boosted by inappropriate technologies and soil erosion which selectively washes out organic colloids from the top soil layers, leading to a vicious circle of a decrease of soil productivity and an increase of soil degradation.

The maintenance of an adequate SOM balance is a complex issue which entails much more than the control of SOM content. It encompasses the whole dimension of sustainable soil management, particularly in the context of settled agriculture under rainfed conditions. There is no shortcut to an integrated approach that recognizes the specific cultural and biological diversity of these areas, understands their complex ecological processes, involves local people at all stages of the development process, and promotes collaboration among biologists, agricultural scientists and social scientists (NRC, 1993). For instance, land tenure issues and rural infrastructure, such as credit and local market organizations, are needed by poor farmers to invest in the preservation of the exploited natural resources. A well designed network of access roads which prevents massive erosive outflows is also central to any sustainable land management system. The strengthening of the national fertilizer sub-sector (FAO, 1987; Schultz and Parish, 1989) requires more attention from national and international decision-makers to address the issue of the nutrient depletion of tropical soils, particularly acute in African farming land (Stoorvogel and Smaling, 1990).

This paper has emphasized adapted technological options, the implementation of which at field and farm levels is the key issue which all the scientific, development and funding agencies should address.

First, the need for an agro-ecological approach implies an **easing of disciplinary boundaries** and an evolution of institutional structures and of the scientific environment with a view to promoting the needed multidisciplinary and participatory approach at ground level. Concretely this approach will be ideally achieved by the progressive development of a common language among specialists, common analysis of experimental results and of a feed-back from beneficiaries, leading eventually to the establishment of a broadly accepted framework for actions related to sustainable land management than can be tested in common projects (Smyth and Dumanski, 1993).

Second, a related question is the identification of boundaries of **land units which are relevant** vis-à-vis the development of adapted improved technologies. Concretely, this means mapping existing land-use systems, merging the traditional soil/landscape major features with information related to land tenure within the boundaries of the 'terroir'/catchment-village mentioned above. Such works can be accelerated, at ground level, by new technologies such as Global Position System and eventually upgraded, at office level, through the implementation of comprehensive GIS. Furthermore, an **assessment of constraints** has to be made at three levels (field, farm and 'terroir') (Tropsoils, 1991; Izac and Swift, 1993), focusing on fluxes of OM and OM balance and on constraints to fertilizer use at the level of farmers and of rural communities (IFDC, 1993).

Third, among improved technologies related to the practical implementation of IPNS, there is a need to focus on the **test and assessment at farm level of direct drilling and conservation tillage** practices, taking advantage of and adapting the results already obtained in Latin America. The soundness and practicality of setting up a Perennial Research and Extension Unit (Séguy *et al.*, 1991) should be appraised as a component of any sustainable land management projects with the final aim of fostering the adoption of new technologies and of decreasing the time span between the local adaptation of these technologies and their dissemination.

Fourth, there is an urgent need to find practical and 'robust' means and tools to monitor changes of land quality related to changes in SOM content, focusing on '**proxies**' and **threshold values** which can be used by project managers and eventually by policy-makers. Yet, information on critical levels of SOM content is scarce in the scientific literature (Sanchez and Miller, 1986). An empirical relationship has recently been proposed, for the kaolinitic and ferric soils of the African savannah region (Pieri, 1992), between the amount of SOM and the surface area of mineral adsorbent, beyond which maintenance of soil structure is at stake. However, this kind of relationship does not address the need for identifying robust indicators which should ideally provide land owners and developers with early warning of ecological deterioration and loss of soil productivity (Hamblin, 1992). The identification of such indicators will surely be influential in determining effective IPNS and improved agricultural productivity in tropical cropping systems.

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SESSION 3

Renewable supply of plant nutrients from natural sources and plant nutrient transfer to crops

Potential and assessment of BNF and its direct contribution in selected cropping systems and ecological conditions

In order to help meet the escalating demand for food resulting from the dramatic expansion of the world's population, mineral fertilizers and pesticides have been used extensively to increase the yield of crops from arable land. However, intensive agricultural methods have introduced undesirable and sometimes catastrophic consequences by polluting air, soil and aquatic systems as well as foodstuffs. Furthermore, a matter of concern is the high cost in terms of fossil energy used in fertilizer production.

The microbial activity in the rhizosphere is partially dependent upon climatic and soil physical factors. The latter can be manipulated to alter soil and plant micro-organism associations. The prevention of harmful factors such as waterlogging, by good drainage, is a prerequisite for efficient nitrogen-fixing symbiosis between *Rhizobium* and legumes. Tillage methods affect many soil characteristics such as aeration, structure, temperature and water regime, all of which affect the microbial balance. Altering the rhizosphere flora by inoculation with certain organisms has long been recognized as a practical possibility. The beneficial effect of rhizobial inoculations on yield and quality of crops and on soil fertility is widely recognized. The use of other bacterial fertilizers, e.g. azotobacter and phosphate-dissolving bacteria, has been also adopted in certain countries. Furthermore, inoculation of non-legume crops by associative nitrogen-fixing azospirilla is promising. Algalization and application of *azolla-anabaena* systems have been evaluated and accepted for application as biofertilizers in rice fields. The purpose of this paper is to define the potential and assessment of BNF and its contribution in selected cropping systems.

NITROGEN FIXING SYSTEMS

The importance of legumes in building and conserving soil fertility has been recognized long ago. With techniques for detecting ability to fix nitrogen such as Kjeldahl, ^{15}N and acetylene (C_2H_2) reduction methods, an increased number of N_2-fixing species have been identified. They include free-living types e.g. bacteria and cyanobacteria; symbiotic systems e.g. rhizobia-legume, angiosperm-actinomycetes, and cyanobacteria-azolla association; and associative systems. These systems have one characteristic in common which is the ability to utilize atmospheric nitrogen but they differ in physiology, metabolic reactions and genetic characteristics.

PAPER 3.1

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TABLE 1

Main taxa of N_2-fixing cyanobacteria (indicating the section of the cyanobacteria to which the groups belong) found in rice soils in South-east Asia (from Roger *et al.* 1987).

Unicellular group Section I	Unicellular strains *(Aphanothece, Gloeothece)*
Anabaena group Section IV	Heterocystous strains with a thin sheath, without branching, do not form mucilaginous colonies of definite shape *(Anabaena, Nodularia, Cylindrospermum, Anabaenopsis)*
Nostoc group Section IV	Heterocystous strains with a thick sheath, without branching, forming mucilaginous colonies of definite shape *(Nostoc)*
Aulosira group Section V	Heterocystous strains with a thick sheath, usually without branching, do not form diffuse colonies on agar medium *(Aulosira)*
Scytonema group Section IV	Heterocystous strains with false branching, without polarity, forming velvet-like patches on agar medium *(Scytonema)*
Calothrix group Section IV	Heterocystous strains with false branching, with polarity, forming velvet-like patches on agar medium *(Calothrix, Tolypothrix, Hassalia)*
Gloeotrichia group Section IV	Heterocystous strains, with polarity, forming mucilaginous colonies of definite shape *(Gloeotrichia, Rivularia)*
Fischerella group Section V	Heterocystous strains with true branching *(Fischerella, Westiellopsis, Stigonema)*

FREE-LIVING NITROGEN-FIXING ORGANISMS

Bacteria: The free-living N_2-fixing bacteria contain organisms of soil, aquatic, phyllosphere and rhizosphere habitats, photosynthetic aerobes, anaerobes and facultative species. Collectively, they are capable of metabolizing a wide range of carbon compounds with a wide pH range extending from 3 to 10. The most dominant genera of this group were stated by La Rue (1977) to be belonging to the families: thiorhodacease (chromatiaceae), athiorhodaceae (rhodospirillaceae), hyphomicrobiaceae, chlorobacteriaceae, spirillaceae, azotobacteriaceae, entrobacteriaceae, corynebacteriaceae and bacillaceae. Cyanobacteriaceae, in particular, attracted special attention due to their agronomic importance in paddy fields.

Cyanobacteria (blue-green algae): The cyanobacteria or blue green algae are photosynthetic bacteria. Some of them are able to fix atmospheric nitrogen. They can be divided into two groups based on growth habit: the unicellular forms and the filamentous forms. N_2-fixing species of the two groups are found in paddy fields in which the heterocystous filamentous forms are the most predominant (Table 1). The trophic independence from carbon and nitrogen, together with a great adaptability to variations of environmental factors, enables cyanobacteria to be ubiquitous. This was demonstrated by a study on soil samples collected from different countries in the Southeast Asian region, India and Africa (Watanabe and Yamamoto, 1971). However, their results indicated that N_2-fixing cyanobacteria are not present in every environment. Of 911 samples only 46 (5%) harboured N_2-fixing species. N_2-fixing cyanobacteria grow more abundantly in tropical and subtropical regions and are less common in temperate and subtemperate regions.

AMOUNTS OF N_2-FIXED

In agronomic trials, crop yields provide an indirect measure of N_2-fixation by cyanobacteria in a particular soil. The algal fixation is estimated to range from 20 to 30 kg N/ha. In modern agricultural practices with high-yielding, fertilizer-responsive rice varieties, increases in crop yield have been observed as a result of algal application. Such phenomena cannot be attributed solely to cyanobacterial nitrogen fixation and presumably a variety of other biological substances synthesized and liberated by these cyanobacteria may have a role to play (Venkataraman and Neelakanthan, 1967; Yanni, 1991b). Other effects were also reported, e.g. prevention of growth of aquatic weeds in rice fields (Subramanyan *et al.*, 1965; Yanni *et al.*, 1988a) increasing the availability of phosphorus (Arora, 1969; Yanni, 1991a; Yanni and Abd El-Rahman, 1993), decreasing sulphide injury (Jacq and Roger, 1977) and aiding particle aggregation (Roychoudhury *et al.*, 1980), incidence of rice infestation with the blast fungus *Pyricularia oryzae* (Yanni and Osman, 1990; Yanni and Sehly, 1991) and the stem borer *Chilo agamemnon* and the leaf miner *Hydrellia prosternalis* (Yanni and Abdallah, 1990); protection of rice against 'rosette long-day' disorder by inoculation with the gibberellic acid producing cyanobacterium *Aulosira fertilissima* (Yanni, 1991b).

TRANSFER OF FIXED NITROGEN

The transfer of fixed nitrogen by cyanobacteria into rice has been well documented. Measurements of the amounts of nitrogen fixed by the ^{15}N-labelled algal cells spread on the soil surface or incorporated into the soil, showed that between 36 and 51% of added N was recovered by rice in the first season (Wilson *et al.*, 1980). Similar pot and field experiments indicated that 23-28% of the N in the ^{15}N-labelled cyanobacteria incorporated into the soil was recovered in the first rice crop whilst only 14-23% was left in the soil (Tirol *et al.*, 1982).

INOCULATION WITH CYANOBACTERIA

The technology of inoculation of rice fields with cyanobacteria or 'algalization' has been developed in India (Venkataraman, 1981). Methods of inoculum preparation and distribution, response to inoculation and factors affecting this practice are reviewed by Hamdi (1982). Results of inoculation are not always encouraging. An average increase of 15% in rice yield was reported under field conditions (Roger and Kulasooriya, 1980). Under Egyptian conditions, inoculation with fresh field propagated soil-based inoculum of cyanobacteria increased rice grain yield by 17-29% (Yanni *et al*,. 1988a, b).

RHIZOBIA/LEGUME SYSTEMS

The Rhizobia: Giller and Wilson (1991) indicated that rhizobial genera include the genera *Rhizobium, Bradyrhizobium, Azorhizobium, Sinorhizobium* and *Photorhizobium*. These genera include the following species :

Rhizobium: fast growing rhizobia :

R. meliloti	isolated from alfalfa.

TABLE 2
Nitrogen fixed by pulses, forage, green manure and shade trees (kg N/ha/yr) (Nutman 1976)

Plant	Average	Ranges
PULSES		
Vicia faba	210	45-552
Pisum sativum	65	52-77
Lupinus spp.	176	145-208
Phaseolus aureus (green gram)	202	63-342
Phaseolus aureus (mung)	61	-
Cajanus cajan (pigeon pea)	224	168-280
Vigna sinensis (cowpea)	198	73-354
Canavalia ensiformis	49	-
Cicer arietinum (chickpea)	103	-
Lens culinaris (lentil)	101	88-114
Arachis hypogaea (groundnut)	124	72-124
Cyamopsis tetragonoloba (guar)	130	41-220
Calopogonium mucunoides (calapo)	202	370-450
FORAGE, GREEN MANURE, SHADE TREES		
Centrosema pubescens (centro)	259	126-395
Desmodium intorum and *D. canum* (tick clover)	897	-
Leucena glauca	277	74-584
Lotononis bainesii	62	-
Sesbania cannabina	542	-
Stylosanthes sp. (stylo)	124	-
Mixes of centro and stylo	115	-
Phaseolus atropurpureus (siratro)	291	-
Mikanea cordata	120	-
Pueraria phaseoloides (kudzu)	99	-
Enterolobium saman	150	-

R. leguminosarum biovar	*Viciae, trifoli, phaseoli.*
R. fredii	fast growing symbiont for soybean.
R. galegae	from pasture *Galega orientalis.*
R. luakuii	from *Astragalus* for green manure.
R. tropica	tropical rhizobia isolated from *Phaseolus vulgaris* that also nodulates *Leucaena* spp.
R. loti	from *Lotus.*
R. etli	from nodulating *P. vulgaris.*

Bradyrhizobium:

B. japonicum	from slow growing soybean rhizobia.

Azorhizobium:

A. coulinodans	produce both root and stem nodules on *Sesbania rostrata.*

Other genera i.e. *Sinorhizobium* and *Photorhizobium* were proposed but the taxonomy subcommittee did not endorse them (Young *et al.*, 1993).

HOST-PLANT

Plant-cross inoculation groups: The concept of a 'cross inoculation group' was developed by Fred *et al.* (1932): a group of legume host species supposedly nodulated beneficially by one set of rhizobial strains and not by any rhizobial strains that induce nodules on legumes not belonging to that particular cross inoculation group. While this concept served a practical purpose in terms of legume inoculant production, many strains which were for a long time considered 'specific' were now found 'promiscuous' i.e. of wide host range. The classical cross-inoculation groups known are: alfalfa, clover, pea and vetch, cowpea, bean, lupine and soybean.

Assessment of nitrogen fixation: There is no simple way to measure N_2-fixation which is particularly difficult in the field. Careful consideration should be given in designing experiments to whether accurate measurements of N_2-fixation or comparative assessments are needed, i.e. N_2-fixed in different treatments or measurements of benefits from fixation i.e. increase in yield or total N content. However, the methods of measurements of N_2-fixation include:

1. *Total nitrogen* by Kjeldahl method.
2. *Activity of enzyme nitrogenase* by acetylene reduction technique.
3. *Analysis of N-transport components* which is based on the fact that newly-fixed nitrogen is transported in plants in the form of amides or ureides, while nitrogen is absorbed from the soil as nitrate or ammonium (ammonium is rapidly assimilated as it is toxic and ureides production is restricted to certain legumes).
4. *^{15}N isotope dilution method* which involves the use of ^{15}N.

Amounts of nitrogen fixed: Various reports have discussed the amount of nitrogen fixed by legumes. In general, pulses fix nitrogen less than forage legumes; however, this depends largely on the crop itself and on factors interfering with the growth of the crop (Table 2, Nutman, 1976). However, the amounts of nitrogen fixed can be affected by many factors (Hamdi, 1982):

1. *Factors related to rhizobia*: infectivity and efficiency of fixation, survival and persistance in soil, competition among rhizobia strains, etc.

2. *Factors related to the host*: host specificity, seed coat diffusates, etc.

3. *Soil factors*: soil pH, moisture, temperature, soil gases, salinity, fertilizers (nitrogen, phosphorus, trace elements e.g. molybdenum, cobalt, boron), toxic chemicals e.g. pesticides.

4. *Biotic factors*: predators, nematodes, protozoa, actinomycetes, fungi, *Bdelovibrio*, insects (*Sitona lineata*).

Rizk (1968) studied the amounts of nitrogen fixed by legumes under Egyptian conditions. Clover was found to be the highest with a total of 238 kg N/ha originated from N_2-fixation during four cuts of clover along with N-content of seeds at harvest. Nitrogen fixation in pulses registered 138 kg N/ha for lupine, 136 for broadbean, 105 for fenugreek, 98 for chickpea, 83 for lentils, 79 for groundnut and 40 kg for soybean.

TABLE 3

Amounts of nitrogen fixed by various legumes under different conditions

Location	Amounts kg N/ha	Notes	References
Soybean:			
Egypt	16.7		Rizk (1968)
Egypt	9.4, 24, 3, 83.7	After 45, 67, 115 days	Abdel Wahab *et al.* (1989)
Arkansas (USA)	56-161		Bahangoo & Albritton (1976)
USA	300	Sandy loam	Bezdrick *et al.* (1978)
USA	38	Fertile soil	Hardy *et al.* (1973)
Greece	22-236		Danso *et al.* (1987)
Romania	17-132		Danso *et al.* (1987)
Percentage N derived from air			
USA	58-95%	Greenhouse	
	7.3-51%	Field experiments	Kohl *et al.* (1980)
USA	39-61%		Senaratne *et al.* (1987)
Cowpea:			
Kenya	50.5-73.7	20 kg fert. N	Ssali & Keya (1985)
	15.3-27.8	100 kg. fert. N	
Australia	59	0 kg Nitrogen	Ofori *et al.* (1987)
	73	25 kg N	
Faba bean:			
Egypt	56.8	Clay loamy soil	Rizk (1966)
Egypt	91.4-113.9	^{15}N method	Abdalla *et al.* (1989)
Austria	140	^{15}N method	Wagner & Zapata (1982)
Percent N derived from air			
Canada	87.1%		Richards & Soper (1979)
Austria	81%		Fried *et al.* (1983)
Egypt	91.4-93.1		Abdalla *et al.* (1989)

Hamdi (1982) reported that in field experiments in 10 locations in Upper Egypt, a significant response of broad bean to inoculation in terms of number and weight of nodules, was observed at 77-91 days after planting. However, significant seed yield responses ranged from 23.5 to 35.8% and were detected in 3 out of the 10 locations while no significant effect on the yield of straw was obtained.

Yanni and Mohamed (1985) reported enhancement of nodulation and N_2-fixation by *R. japonicum* in soybean as a contribution of the asymbiotic N_2-fixer *Azotobacter chroococcum*.

Papastylianou (1988) reported on the results of studies for 6 years on response to inoculation in several legumes. Common vetch, faba beans, ochrus vetch and medics can gain from 36 up to 84% of their nitrogen content from inoculation. Results of Yanni and Mohamed (1985), Yanni *et al.* (1987; 1990), Abdel-Hafez and Yanni (1988) and Yanni (1990) reported increases ranged from 33.1 to 114% depending upon rate of N-fertilization, addition of micro-elements, sowing dates, combined inoculation with asymbiotic N_2-fixer and different soil salt-stress in soybean yield due to inoculation with *B. japonicum*.

Solh (1988) showed that in Begaa's plain (Lebanon) inoculation of chickpeas and lentils did not increase yield although nodule dry weight was increased significantly. Apparently the exogenous rhizobia were less efficient than the endogenous rhizobia. Lupins responded to inoculation and gave 45% and 75% increases in the local and Giza II varieties. Yanni (1992c) reported increases of 35, 205 and 203% due to inoculation of lentil, chickpea and lupin in Nile Delta each with its corresponding rhizobia, respectively.

A summary of the results from different parts of the world is presented in Table 3.

In general, the amounts of nitrogen fixed vary from one crop to the other according to location, plant-rhizobia system and environmental conditions. However, these data clearly illustrate the contribution of nitrogen fixation process to the legume-rhizobia system.

Transfer of nitrogen to companion plants: Giller and Wilson (1991) summarized the possible mechanisms by which legume nitrogen can be transferred into other plants. In below-ground plant parts, nitrogen can be made available by root and nodule sensecence, rhizodeposition or root exudates through active secretion, passive loss or sloughed off cells, or direct transfer between roots by interconnected microrhizobial strands. Nitrogen can be made available also through the above-ground plant parts by fallen leaves, leachates, ammonium loss and uptake by associated plants and by plant residues. Whitney (1975) discussed nitrogen fixation by legume-grass mixtures such as *Desmodium intorum, D. canum* and *Centrosema pubescens* with and without pangola (*Digitaria decumbens*) and napier (*Pennisetum purpureum*) grasses. He found that net nitrogen-fixation, including secretion of nitrogen in the root mass, was low for *D. canum* except for the mixture with napier grass. *Centrosema pubescens* was intermediate in result, but in nitrogen-fixation with grass was also low. *D. intortum* was effective in fixing nitrogen (supplying about 400 kg N/ha/year in pure stand and only slightly less in the grass-legume mixture). In addition, in another study nitrogen fixed and transferred between *Desmodium* and pangola grass was determined. *D. canum* fixed nearly 100 kg N/ha/year, of which an estimated one third was transferred into the pangola grass. Although *D. intortum* fixed 264 kg N/ha/year, it transferred only slightly more nitrogen to the grassland than did *D. canum*, amounting to one eighth of the total nitrogen fixed. *D. intortum* in pure stands fixed the most nitrogen.

Matova (1985) indicated that nitrogen has been transferred from *Albizia* spp (legume tree) into coffee plants (*Coffee canephera*) and the yield of coffee has been increased accordingly by 1.7, 13.7, 21.9 and 101% in seasons 1875/76, 1976/77, 1977/78 and 1978/79, respectively.

Most evidence for significant benefits of N transfer has been based on the N-difference method or on an isotope dilution in which a companion of isotope enrichment of pure or mixed grass sward is made after the soil has been labelled by ^{15}N enriched fertilizer. Estimates of 20-50% (Ta and Faris 1987) to over 80% of the grass N being derived from legume (Broadbent *et al.* 1982). A direct method of measuring transfer in which labelled N is applied to the leaves so that any subsequent detection of it in the grass gives direct evidence of N transfer. Ledgard (1991) estimated under ground transfer of N between clover and rye grass of 70 kg N/ha, as compared to clover which fixed 270 kg N/ha annually.

LEGUMES IN ROTATION WITH CEREALS

The residual effect of legumes on subsequent crops is one of the most important factors to be considered when they are introduced into a farming system. Another important factor is their high protein yield which is important for human and animal nutrition. These factors were studied in rotation experiments in two locations in Cyprus (Papastylianou, 1988). Grain

TABLE 4

Amount of nitrogen fixed by leguminous crops and their influence on a following cereal crop (after Russell, 1961)

Crop	Nitrogen harvested in		Gain or loss of nitrogen in the soil kg/ha	Total nitrogen fixed by legume kg/ha	Yield of cereal grain cut kg/ha
	Leguminous crops kg/ha	Cereal crops kg/ha			
Lucerne	335	74	137	504	26.0
Clover	140	57	129	291	21.7
Sweet clover	190	57	94	302	21.2
Soybean	197	33	-9	179	13.2
Field beans	115	28	-22	78	11.9
Cereal every year	-	25	-11	-	3.0

TABLE 5

Changes in soil nitrogen cultivated with legumes and non-legumes (after Rizk 1968)

Crops	Stage of growth	Change, kg N/ha
Legumes		
Broad bean	Immature	-10
Lentil	Mature	+34
Lentil	"	+86
Fenugreek	"	+166
Termis (lupine)	"	+122
Chickpea	"	+91
Groundnut	"	+82
Soybean	"	+58
Berseem fahl	Single cut	+101
Berseem miskawy	4 cuts	+259
Non-legumes		
Barley	Immature	-26
Barley	Mature	+7
Sesame	"	+38
Chickoria	4 cuts + seeds	+22

yield of barley after vetch is compared with grain yield in a continuously barley growing system. The data show that (a) barley after vetch without nitrogen fertilizer can yield as much as continuously cropped barley with 60 kg N/ha, (b) barley fertilized with high nitrogen in continuous cropping cannot yield as much barley after vetch when in the latter system barley is fertilized with 30 kg N/ha and (c) high doses of nitrogen fertilizers (above 60 kg N/ha) caused yield reduction in both rotations.

Russell (1961) presented the results of a two-year rotation of legume-cereal, the cereal being either rye or barley (Table 4). They show that the yield of the following cereal crop largely depends on the amount of nitrogen the legumes add to the soil. The amount of nitrogen fixed varies from 78 to 504 kg/ha. Leguminous crops grown for seed (peas, field beans, soybeans and groundnuts) show a tendency to reduce the nitrogen content of the soil, whereas legumes grown for their leaf (clovers, sweet clover, and lucerne) increase the nitrogen content.

TABLE 6

Amounts of nitrogen accumulated by green manure legumes and incorporated into the soil as above-ground plant residues (Giller and Wilson, 1991)

Species	N accumulated (kg/ha)	Country	Period of growth (days)
Aeschynomene americana	170	USA	120
Canavalia ensiformis	108	Brazil	150
Cajanus cajan	190-250	USA	150
Crotalaria juncea	23	Brazil	150
	198	Indonesia	90
	99	India	unknown
C. spectabilis	160	USA	120
	106	USA	70
Indigofera hirsuta	220	USA	150
Lablab purpureus	78	USA	70
Mucuna aterrima	86	Brazil	150
M. deeringiana	190	USA	120
M. pruriens var. utilis	71	Indonesia	90
	110	Nigeria	98
Psophocarpus palustris	81-106	Nigeria	unknown
	42	Nigeria	98
Sesbania spp.	24-206	India	57
S. sesban	39-85	India	100
	120	India	200
Vigna radiata	40	USA	120

Rizk (1968) reported that the nitrogen content of the soil varies according to the crop cultivated. As indicated in Table 5, the increase of nitrogen in soil varies between 34 and 259 kg/ha with legumes but, with non-legumes like barley, sesame and chickoria, the nitrogen content varies between 7 and 38 kg/ha. It is apparent that non-leguminous plants reduce nitrogen contents in the soil during the growth period.

A series of field experiments on nitrogen fertilization after non-leguminous crops and after berseem showed that paddy transplanted in soils previously cropped with non-legumes was more responsive to added nitrogen than after clover. Yields of rice after non-legumes gradually increased as the rate of nitrogen increased up to 96 kg/ha, whereas, the yield of paddy after clover reached its maximum at 24 kg N/ha (Serry *et al.*, 1970).

LEGUMES AS GREEN MANURE

Green manure legumes are those grown wholly for use as organic manure for a subsequent crop. Green manures are ploughed in whilst the plant material is still green and have higher nitrogen and moisture contents than grain legumes, both factors which will favour rapid mineralization. The usefulness of legume green manures in maintaining or building up soil fertility has long been recognized. The amounts of nitrogen accumulated by various green manures are presented in Table 6 (Giller and Wilson, 1991).

Uptake of residual N of green manure on the following crop varies from one system to the other. The first crop of rice recovered 33% of N supplied by *Sesbania* green manure but

TABLE 7
Classification of non-leguminous nitrogen-fixing angiosperms (Becking, 1977)

Order	Family	Genus	Number of symbiotic species. In parenthesis number of species
Casurinales	Casurinaceae	*Casuarina*	18 (45)
Myricales	Myricaceae	*Myrica*	20 (35)
		Comptonia	1 (1)
Fagales	Betulaceae	*Alnus*	33 (35)
Rhamnales	Elaeagnaseae	*Elaegnus*	14 (45)
		Hippophae	1 (3)
		Shepherdia	2 (3)
	Rhamnaseae	*Ceanothus*	31 (55)
		Discaria	2 (10)
		Colletia	2 (12)
Coriariales	Coriariaceae	*Coriaria*	13 (15)
Rosales	Rosaceae	*Dryas*	3 (4)
		Purshia	2 (2)
		Cerecarpus	3 (20)

TABLE 8
Field measurements of nitrogen-fixation in some non-legumes (Becking, 1977)

Non-legume	Nitrogen-fixation kg N/ha/yr
Casurina equisetifolia	229
Myrica cerifera	3.4
M. rubra (3-15 yr old)	15.25[1]
Alnus crispa (50 yr old)	61.5
A. crispa	40.0
A. crispa (5 yr old)	157.0
A. glutinosa (0-7 yr old)	
(1 plant/m^2)	28.0
(5 plants/m^2)	100.0
A. glutinosa (12 yr old)	26-28.0
A. glutinosa	58
A. incana	40
A. rubra	139
A. rubra	up to 300
A. rugosa	193
A. rugosa (natural stand)	85
Hippophae rhamoides (0-3 yr old)	27
(13-16 yr old)	179
H. rhamoides (1-2 yr old)	2
(10-15 yr old)	15
Geanotus spp. (natural shrub community)	
Drys drummondii	60
D. drummondii	18-36
Some *Shepherdia canadensis*	61.5

[1] Data from comparison of *Myrica* pine stands and pure pine stands. Nitrogen-fixation determined by subtracting total amount N pine stand from total amount N *Myrica*-pine stand.

only 21% of N added by green manure *Crotalaria juncea* (Rao and Shinde, 1991). More than 70% of the N in shoot of cowpea was recovered by six successive crops in cowpea/rice/soybean or cowpea/rice/maize rotation (Sisworo *et al.* 1990). Green manuring of maize with *Crotalaria juncea, Canavalia ensiformis*, or *Stizolobium deeringianum* corresponded to the addition of 60 kg N/ha/yr of fertilizer N, but the economics of this did not compare favourably with adding higher levels of mineral nitrogen fertilizer. Dobereiner and Campelo (1976) registered the superiority of *Crotalaria juncea* over other legumes and sorghum as a green manure for field beans, *Phaseolus vulgaris*.

NODULATED NON-LEGUMINOUS PLANTS

The nodulated non-leguminous plants are perennial angiosperms which bear nitrogen-fixing root nodules. The first evidence that such plants fix nitrogen was obtained by Hiltner in 1896 who studied *Alnus glutinosa* (Stewart, 1976). Detailed knowledge of the morphology, physiology and bio-chemistry of these nitrogen-fixing plants has become available through the work of several investigators (Bond, 1974; Quispel, 1974; Becking, 1977; Akkermans, 1978).

The macro-symbiont and the extent of nitrogen fixation: The orders, families and genera known to be nodulated are presented in Table 7. Nitrogen fixation measurements of some non-legumes (Table 8) are stated by Becking (1977). The data show different N_2-fixation capacities ranging from 2 to 30 kg N/ha/year depending on the type, age and location of the plants.

The microsymbiont: The microsymbiont is an actinonorhizal endophyte genus *Frankia*. This genus has 10 species named after the host plants.

Amounts of nitrogen fixation: Nitrogen fixation measurements are presented in Table 8 (Becking, 1977). The data show different N_2-fixation capacities ranging from 2-30 kg N/ha/year depending on the type, age and location of the plants.

AZOLLA

The aquatic fern azolla is always found in a N-fixing symbiosis with the cyanobacterium *Anabaena azollae*. It is common in tropical and temperate climates. Six species have been taxonomically classified. Three of them (*A. filiculoides, A. caroliniana* and *A. mexicana*) are indigenous to the temperate regions of North America. A fourth species, *A. microphylla*, reported in the extreme southeastern USA, may be a recent introduction from tropical areas of the Caribbean to North America. *Azolla pinnata* is commonly found in India, China, Viet Nam and the Philippines. *Azolla nilotica* is a large species occurring in the Nile in Africa.

Overall environmental requirements: The overall environmental requirements of azolla are so interrelated that it is often difficult to single out one factor. It is obvious that water is a prerequisite for life for an aquatic fern and for mineral uptake from the medium. Likewise processes like growth and N_2-fixation depend on temperature and the qualitative and quantitative presence of light, gases, etc.

TABLE 9
Nitrogenase activity on and in the roots and in the rhizosphere soil of tropical forage grasses (Day, 1975)

	C_2H_4/g dry roots/hr nano mole	C_2H_4/g soil/hr nano mole
Brachiaria mutica Brazil	156-730	0.0
B. rugulosa (Tanner grass)	5-148	-
Hyparrhenia rufa	17-29	0-0.148
Digitaria decumbens	21-404	0-0.349
Pennisetum purpureum	5-954	0-0.085
Panicum maximum	20-294	0-0.148
Melinis minutuflora	13-41	0-0.187
Cynodon dactylon	17-269	0-0.168
Paspalum notatum (Batatais)	2-283	0-0.330
Andropogon gayanus Nigeria	15-270	-
Cenchrus ciliaris	16	-
Cymbopogen giganteus	60-85	-
Cynodon dactylon	10-50	-
Cyperus spp.	2	-
Hyparrhenia rufa	30-140	-
Hypothelia dissoluta	10-15	-
Panicum maximum	75	-
Paspalum commersonnii	25-30	-
P. virgatum	3	-
Pennisetum purpureum	60	-
P. colaratum	13	-
Setaria anceps	1-120	-
Andropogon Côte d'Ivoire	50-380	-
Brachiaria brachulopa	100-140	-
Bulbsylis aphyllanthoides	74	-
Cyperus obtusiflorus	30-620	-
C. zollingeri	50-160	-
Cyperus sp.	1150-1900	-
Fimbristylis sp.	80-190	-
Hyparrhenia dissoluta	2-4	-
Loudetia simplex	54	-

Amounts of Nitrogen Fixed: Green manuring with azolla (Talley *et al.*, 1977; Watanabe *et al.*, 1977; Varghese, 1990; Yanni, 1992a, b) has rapidly developed from a botanical curiosity to an agronomically important N source. The benefits of green manuring of rice with azolla are not restricted to its capacity to contribute biologically fixed N. Other benefits also occur: the azolla canopy can inhibit growth of aquatic phototrophs and depress photo-dependent CO_2 uptake. Consequently, floodwater pH will not increase during the day and this reduces N loss by ammonia volatilization (which is often high in the summer season) especially when high amounts of fertilizer N are applied to rice fields (Singh, 1977a, b).

The soil and water resources of Egypt have, until recently, been completely free of azolla. Trials on its utilization for enhancing rice performance in the Nile Delta were started in 1977 using imported fern (Hamdi *et al.*, 1980). Some contradictions and difficulties faced this new technology. The most important of them was the relatively large amounts of azolla needed for inoculation of a limited field area; demand for large scale production facilities; and difficulties of preservation and transportation of the fern to be stored and used fresh for inoculation of rice fields (Yanni, 1992a, b). Because of the fern escaping from its nurseries during field experiments carried out during 1983 to 1986, it is now a natural inhabitant in stagnant water of most of the drainage canals all over the Nile Delta. Because of this event, the problems of inocula production, preservation, transportation and survival for large-scale utilization of the fern for green manuring of rice have largely been solved. In 1990, experiments were conducted to use this new indigenous azolla for green manuring of rice. Although green manuring of rice fields with azolla enhanced rice performance and compensated for application of 1/3 to 1/2 of the recommended amounts of fertilizer N for rice, the results revealed the need for relatively high quantities of the fern as positive response of rice yield was observed even with green manuring with 6 tons fresh *Azolla caroliniana*/ha (Yanni, 1992a). However, inoculation with azolla at 2 ton/ha fresh fern along with incorporation of the propagated azolla during hand weeding at 20, 40 and 60 days after transplanting enhanced rice performance and saved up to 1/2 of the recommended fertilizer N for each of some of high N-responsive Indica rice varieties and Japonica low N-responsive ones.

Although these studies falls into the 'black box' category of research about utilization of azolla in enhancing rice performance, in which the positive effects derived are interpreted mainly by indirect evidence, the practice which is introduced in this work seems simple, economical and may lead to minimizing the needed quantity of azolla for green manuring of rice by using a small starter inoculum of indigenous azolla with incorporation up to three times during hand weeding of the rice field.

ROOT ASSOCIATED NITROGEN FIXING BACTERIA

The association of *Azospirillum brasilense* (Syn. *Spirillum lipoferum*) with roots of grasses and other economically important plants has been well documented (Bulow and Dobereiner, 1975; Baldani and Dobereiner, 1980). The beneficial effects of *Azospirillum* inoculation on the yield of non-legumes have been reported (Subba Rao *et al.*, 1979). Sampaio *et al.* (1978) indicated that there are three groups of isolates of *S. lipoferum* based on the physiological characteristics, especially nitrate reduction. However, Krieg (1977) suggested the generic name *Azospirillum* and named two species: *A. lipoferum* and *A. brasiliensis*. Accumulating evidence shows that *A. lipoferum* is present on the surface as well as inside the roots of maize, *Digitaria* and other grasses (Dobereiner, 1978; Burris, 1977). Studies with N^{15} have shown that the organism is capable of autonitrogen-fixation. The nitrogenase activity of washed roots of field grown tropical grasses are summarized by Day (1975) in Table 9 which shows large variation exists between sites, species and sampling times. Maximum values were found for *Pennisetum purpureum*, if transformed into fixed nitrogen, indicating fixation of up to 1 kg N/ha/day. Activity was associated mainly with roots and little was noted in the soil.

The major associative nitrogen-fixing systems currently described are presented in Table 10. *In vitro* studies show that many of the bacteria can achieve high rates of nitrogen-fixation under optimum conditions. However, in the rhizosphere estimated nitrogen fixation is extremely variable.

Response of several crops to inoculation with *S. lipoferum* was studied by Smith *et al.* (1975). Inoculation produced significantly higher protein and dry matter yields in *Pennisetum americanum* and *P. maximum*. Projected yields using regression analysis of both crops indicated that about 40 kg N/ha/year were replaced by inoculation. Response to inoculation

TABLE 10

Major associative diazotrophs (Raschel and Vose, 1984)

Plant species		Principle micro-organism
Rice: *Oryza sativa*		*Achromobacter, Enterobacteriaceae, Azospirillum brasilense*
Sugar cane: *Saccharum* spp.		*Azotobacter, Beijerinckia, Bacillus, Klebsiella, Derxia, Vibrio, Azospirillum, Enterobacteriaceae, Bacillaceae*
Pearl millet and sorghum: *Pennisetum purpureum*		*Azospirillum, Bacillus polymyxa, Klebsiella, Azotobacter, Derxia, Enterobacter*
Maize: *Zea mays*		*Azospirillum lipoferum, Azotobacter vinelandii*
Grasses:	*Paspalum notatum* var. *batatais*	*Azotobacter paspali*
	Panicum maximum	*Azospirillum lipoferum*
	Cynodon dactylon	*Azospirillum lipoferum*
	Digitaria decumbens	*Azospirillum lipoferum*
	Pennisetum purpureum	*Azospirillum lipoferum*
	Spartina alterniflora Loisel	*Campylobacter*
Wheat: *Triticum* spp.		*Bacillus polymixa*

was enhanced at higher rates of nitrogen fertilizer application, e.g. 80 and 120 kg N. On the other hand, some reports referred to very little or no response to inoculation with spirella (Burris, 1977). In some cases, increases due to application of *Azospirillum* are statistically not-significant but they were definitely in a positive direction towards benefit from inoculation. Use of such data to calculate yields and increases in nitrogen on a per hectare basis indicates a possible increase in total nitrogen of 2 to 5 kg/ha during a growing season (Hamdi, 1982).

Under Egyptian conditions *Azospirillum* is found to be a ubiquitous inhabitant of soil and rhizosphere of major Egyptian crops. Application of organic matter with wide C/N ratio was found by El-Haddad *et al.* (1993) to stimulate the proliferation of indigenous *Azospirillum* population in the rhizosphere of growing plants. The synergistic interaction between the organism and the host plants in laboratory studies was attributed to a prolonged nitrogenase activity combined with better utilization of low concentrations of root exudates in the presence of CO_2 and production of growth promoting substances. The contribution of N_2-fixing bacteria, including *Azospirillum*, in nitrogen nutrition of the inoculated plants was extensively confirmed using a nitrogen tracer technique. The benefits and/or economic advantages for inoculation were reported for wheat, maize, rice, sorghum, cotton, tomato, onion, cowpea, soybean, rape and Egyptian henbane.

Recently, Dobereiner *et al.* (1993) reported that sugar cane cultivars CB 45-3 and SP 70-1143 produced 244 and 182 t/ha/yr, respectively, obtaining 154 and 134 kg N/ha/year (as 60% of N-fixed) from the air. Isolates of *Acetobacter diazotrophicus* and *Herbaspirillum* spp. were obtained from sugar cane roots, stems and leaves. *A. diazotrophicus* was found in association with sweet potato (roots, tubers, leaves) but was not found in association with rice, maize, sorghum and certain weeds. *Herbaspirillum* spp. was present in the roots of these plants. This type of endophytic diazotroph-endophytic association needs further investigation.

STEM NODULES

Within leguminosea, certain aquatic legumes and excess water-tolerant legumes are known to bear nitrogen-fixing nodules on stems. These stem nodules are caused by *Rhizobium*. Only some species of *Aeschynomene* and *Sesbania* are known to bear stem nodules. Recently, renewed interest in these nodulating plants has been evidenced in view of the potential benefit that could be derived if similar stem nodules could be induced on cultivated plants. In a recent survey on stem nodulation of legumes, nitrogen-fixing stem nodules have been reported on ceasalpinaceous plants. Similarly, nitrogen fixation has been recorded in warty lenticellate barks of various trees inhabited by enterobacteria (Yatazawa *et al.*, 1981). However, *Sesbania* seems to be the most important stem nodulated plants attracting attention as a very promising N contributor to rice in the tropics (Subba Rao and Yatazawa, 1984).

There are about 20 species of *Sesbania* distributed in the tropics. They are soft-wooded shrubs or herbs. The plants are grown as hedges, the wood is used for making gun-power charcoal, the fibre made into ropes and the foliage used as cattle feed. *Sesbania rostrata* is an annual plant which grows in flooded soils of the Sahel region of the West Africa during the rainy season, thriving in wetland rice fields. Stem nodulation in this plant has been reported by Dreyfus and Dommergues (1981). Nodules occur at the sites of lenticels. They appear 2 m above water level and are usually spheroidal and vary from 0.3 to 0.8 cm in size. The structural features of these nodules resemble other *Rhizobium*-induced nodules of soybean or cowpea, except that the nodule cortex is green due to chlorophyll. Exceptionally high values of 589 um C_2H_4/h/plant have been recorded in stem nodules. The root nodules which are smaller than their counterparts on the stem exhibit less nitrogenase activity. A strain of *Rhizobium* isolated from *S. rostrata* nodulated its homologous host and produced effective nodules on roots and stem but induced ineffective nodules on *S. pachycerpa* and *S. aculeata* and did not nodulate roots of *Aeschynomene* sp. and *Macroptilium atropurpureum*. When a strain of *Rhizobium* isolated from nodules of *S. pachycarpa* was inoculated to *S. rostrata*, it produced ineffective nodules whereas strains of *Rhizobium* isolated from stem nodules of *Aeschynomene* sp. and cowpea did not induce nodulation on *S. rostrata*.

Potentialities: As a green manure crop, *Sesbania* appears to be a good candidate in wetland rice cultivation. In Senegal, it has been estimated that *S. rostrata* contributes 267 kg N/ha of which one-third is transferred to the rice crop and the remainder is left behind in the soil for subsequent utilization. The grain yield of rice was estimated to be 3.72 t/ha with application of *S. rostrata* (Rinaudo *et al.*, 1983).

In inter- and multiple-cropping schemes, legumes are often used under irrigated conditions. There is a distinct possibility for selecting genotypes of legume species which possess a tendency to bear nodules on the hypocotyl or the crown region of the shoot system so that effective utilization of exposed plant surface is done to maximize biological nitrogen fixation.

At the level of fundamental research, stem nodules offer a challenging and convenient system to investigate for the inter-relationship between photosynthesis and biological nitrogen fixation. The cortex of stem nodules is green due to chlorophyll and the bacteroid tissue is pink possibly due to leghaemoglobin. The transfer of carbon skeletons from the cortex into the bacteroid tissue for the process of nitrogen fixation can easily be traced and measured with accuracy by the use of labelled carbon.

NODULATION OF NON-LEGUMES

The extension of the nodulation ability of *Rhizobium* to non-legume crops such as maize, wheat and rice has attracted considerable interest during the past two years. Undoubtedly, the generation and exploitation of new nitrogen fixing symbiosis with these crops is an important research goal. However, the advances obtained up till now have been rather limited.

Structures, instead of nodules, can be more properly defined as lateral root growth. These structures have been observed in roots of maize, wheat and rice (Cooking *et al.*, 1992; Xu *et al.*, 1993; Malik *et al.*, 1993). Microscopic examination of these structures showed that *Rhizobium* cells are mostly located in intercellular spaces and intracellularly. Nitrogen fixation by these structures is not consistent. Further work is needed to assess the practical significance of these structures.

CONCLUSIONS AND RECOMMENDATIONS

From this review, it is evident that nitrogen fixing systems, e.g. free living, symbiotic and associative systems, contribute significant amounts of nitrogen fixed. Rhizobia-legume systems fix nitrogen at the range of 50-300 kg N/ha. Cyanobacteria fix about 15-25 kg N/ha. Azospirillum-grass association may fix between 10-30 kg N/ha. Efforts should be consolidated to make use of these potentials in selecting an integrated plant nutrient policy for plant production. The following recommendations are presented :

At the national level:

- Governments should encourage researchers to study the contribution of each system in agricultural production.
- Establish laboratories for inoculant production for legumes and rice.
- Encourage the adoption of rotations including legumes, intercropping and use of green manures.
- Make use of nitrogen fixing trees.
- Study interaction of nitrogen fixing systems with fertilizers and develop recommendations.

At the regional level:

Cooperation at the regional level in terms of training and exchange of genetic materials, e.g. micro-organisms, germplasm, etc.

At the international level:

FAO should assist member countries in their efforts to study the role of BNF in agriculture through:

- TCP projects to establish laboratories for inoculant production.
- Training of scientists in the area of BNF.
- Workshops and seminars dealing with production and application of inoculants.
- Dissemination of information and assistance in exchanging biological materials e.g. micro-organisms and germplasm.

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Plant nutrient supply by rain, dust, irrigation water and sedimentation – available evaluations

Cooke (1967) describes the fertility of soil as being normally considered as "its potential to support the climax population of plants and animals above ground, and the associated flora and fauna below ground". When the natural ecosystem is disrupted and the soil transformed to agricultural use, the soil's fertility becomes its capacity to produce the crops required. This concept of fertility must encompass a range of phenomena related to the soil. These will include biological properties of the soil, such as the role of soil micro-organisms in the breakdown and transformation of organic residues added to the soil, physical properties such as the porosity of the soil and its influence on water entry, water storage and the ease of root penetration, and the chemical properties that relate to the soil store of nutrients required to sustain plant growth and the availability of these nutrients. In many contexts it is the latter component that is taken as being synonymous with soil fertility, but this grossly oversimplifies the interrelationships and to an extent the interdependence of these components.

PLANT NUTRIENTS

Crop growth, defined as the increase in the size of the plant, either in terms of dry weight or in terms of dimensions, arises as a consequence of the formation of new cells, the expansion of constituent cells, and the production of assimilates. For a green plant to increase in dry matter, atmospheric CO_2 and water within the plant must be chemically combined to form sugars and then a wide range of more complex molecules. Photosynthate produced in the leaves is combined with minerals absorbed by the roots to produce the compounds necessary for plant growth. Initially the source of these nutrients may be from the seed, but the bulk of the mineral nutrient requirements is taken up from the soil via the roots. These nutrients may be available in the soil through natural weathering or added to the soil through inputs of water, organic and mineral deposition or by direct addition of fertilizers or manures. In general, if a well-balanced supply of nutrients available to plants is increased, the amount of plant growth will increase. This increase will rise to a maximum value, beyond which there may be no further increases in growth with increases in nutrient supply, and in some cases further increases in the supply of nutrients may have harmful effects resulting in a reduction in crop growth. For this increased growth to occur there must be an appropriate range of plant nutrients available. Early work on plant nutrition suggested that low levels of any one of the plant nutrients would limit growth, but as knowledge has increased it has become apparent that, because of the often complex interactions between the individual plant

PAPER 3.2

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TABLE 1
Amounts of major nutrients removed in crops

	% dry matter at harvest	kg/t dry matter					
		N	P	K	Ca	Mg	S
Cereal - grain	85	20	4	6	0.6	1.5	1.5
- straw	85	7	0.8	8	3.5	0.9	1.1
Potato - tubers	22	14	1.8	2.2	0.9	0.9	1.4
Oilseed rape grain	92	36	7.6	9.8	4.0	2.5	9.8
Grass - silage	20	32	3	20	6	1.5	1.5
- hay	85	16.5	3.1	17.6	4	1.2	1.2
Kale	15	24	3.3	28	20	2.0	6.0

nutrients, these simple relationships may not hold. Indeed even where several of the nutrients may be in low but not excessively low supply, increasing any one of them may increase plant growth.

In general all higher plants require the same suite of nutrients. Arnon and Stout (1939) described an element essential for plant growth if: (a) a deficiency of it makes it impossible for the plant to complete the vegetative or reproductive stage of its life cycle; (b) such deficiency is specific to the element in question and can be prevented or corrected only by supplying the element; and (c) the element is directly involved in the nutrition of the plant quite apart from its possible effects in correcting some unfavourable microbiological or chemical condition of the soil or other culture medium.

The elements now considered essential for higher plant growth are as follows:-

- ***Macronutrients***: carbon, hydrogen, oxygen, nitrogen, phosphorus, potassium, calcium, magnesium, sulphur.
- ***Micronutrients***: iron, manganese, copper, zinc, boron, molybdenum, chlorine.
- ***Beneficial elements*** include cobalt, sodium and silicon.

Of these, carbon, hydrogen and oxygen are obtained from the atmosphere and water, and they account for 90-95% of plant dry matter. The mineral macronutrients are chiefly obtained from the soil, either directly as a result of weathering of the soil materials, or indirectly from materials added to the soil through natural processes such as precipitation and dry deposition or artificially through the addition of fertilizers and manures. These are often divided into two groups:

- nitrogen, phosphorus and potassium;
- calcium, magnesium and sulphur.

The first group are often taken up in large amounts and most fertilizers added to the soil have one or more of these three as major components. Deficiencies of one or more of these three are common and, in low input systems, contributions from natural sources such as precipitation, dust and dry deposition for example, may have a significant impact on the sustainability of crop growth, albeit at low levels of productivity, making important contributions to the overall nutrient budgets. The second group are taken up by plants in small amounts, and whilst deficiencies are rare there may be some situations where plant growth is restricted by deficiencies in one or more from this group.

The situation with respect to the micronutrients is complex, with the trace elements iron, manganese, copper, zinc, boron, molybdenum and chlorine being required for the growth of higher plants. Cobalt is required for some biological nitrogen fixation systems, such as nodulation in legumes. Sodium is probably not an essential nutrient, but it appears to have beneficial effects on the growth of some plants, for example sugar beet.

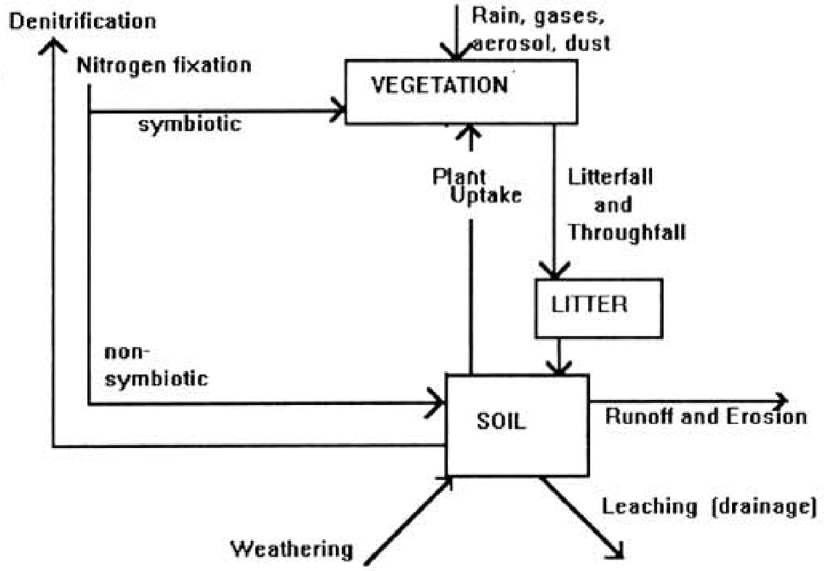
In the management of any plant nutrient system where the aim is to sustain the output, it is essential that the outflow of nutrients is monitored. To maintain productivity it is normally a prerequisite that the export of nutrients be balanced by the import of equivalent amounts. Table 1 illustrates a summary of nutrient export in cropping systems involving a range of crops (Archer, 1988).

NUTRIENT CYCLING

In naturally vegetated ecosystems the nutrient cycle involves, in its simplest form, the transfer of nutrients from soil → plant → animal → soil. There are two major pools of nutrients, the soil and the vegetation, with fluxes between these pools in the form of plant uptake and litter fall and organic decomposition. There are also other additions to the pool, the relative importance of which depends upon the nutrients under consideration (Frissel, 1978). Additions include nutrients released from the weathering of soil and rock material, through rainfall, aerosol and dust deposition, and specifically with respect to nitrogen, additions through symbiotic and non-symbiotic fixation via the plant and soil respectively. The losses from the system will include losses from leaching through the soil, losses through runoff and associated particulate and solute erosion, and again specifically with respect to nitrogen, denitrification losses. These pools and fluxes are illustrated in Figure 1. The magnitude of the pool and fluxes will vary considerably depending upon the ecosystem under consideration as will their relative importance.

Once any part of the ecosystem is disrupted by the harvesting of the vegetation, either initially as with the deforestation of forested lands, or subsequently with the replacement vegetation planted on deforested lands, there is a net export from the system. If the output of the system in terms of the harvesting of products is to be maintained, this is dependent on the soil's ability to provide sufficient nutrients to sustain this growth. In some situations, particularly if the output (harvest) is low and the soil is rich, this may be possible, but in many systems this is only achieved by the supplementation of the nutrient pool from applied mineral fertilizers. This has been the strategy in most advanced agricultural systems, although recently there has been an increasing trend to replenish part of the nutrient pool from the recycling of organic constituents, even though the availability of organic manures and residues is normally not sufficient to satisfy the plant requirements fully. In systems where

FIGURE 1
Schematic representation of a simple nutrient cycle



high levels of external inputs are not possible, the contributions identified in the functioning of the nutrient cycle in the natural ecosystem become increasingly important, in particular the contributions from weathering, from nitrogen fixation and from atmospheric inputs of rain, and aerosol and dust deposition. The relative magnitudes of the inputs from atmospheric sources are discussed below but, by way of a general summary, Table 2 lists levels of major and minor nutrients contributed from atmospheric inputs in England on an annual basis.

TABLE 2
Amounts of nutrients deposited from the atmosphere in England by wet and dry deposition (from Archer, 1988)

	kg/ha/yr		kg/ha/yr
Nitrogen	10.0	Iron	2000
Phosphorus	0.3	Manganese	100
Potassium	3.0	Boron	150
Calcium	10.0	Copper	100
Magnesium	5.0	Zinc	500
Sulphur	25.0	Molybdenum	10
Sodium	10.0	Selenium	3
Chlorine	20.0	Cobalt	2

In natural systems the losses in the form of runoff and leaching to groundwater are often small, but once disruption takes place through agricultural development, substantial losses may occur and these must be controlled, although the losses in leaching and runoff may become important inputs at other locations in the system and, in the absence of significant data on the inputs from these sources, data on the nature of leaching and solute losses are used as surrogates for these data. Leaching may be considered as deep and shallow losses. Deep losses to groundwater may be substantial and there is considerable concern in many countries about the potentially harmful effects of leached nutrients and other agrochemicals in groundwater supplies used for human consumption. It should be noted that where these groundwaters as irrigation sources there is a partial recycling of the lost nutrients. A similar recycling may occur where losses in the form of runoff are used as irrigation supplies. Where shallow leaching is the main form of leaching loss this may have local significance as a nutrient source if there is any significant element of throughflow or interflow. Shallow leaching losses in upper landscape positions may make significant contributions to the nutrient budgets in lower landscape positions, and a number of agricultural communities have adopted these natural processes in the design and management of their agricultural production on a landscape basis.

NITROGEN

Nitrogen is of particular importance in plant nutrition. In most systems where there is sufficient water to satisfy plant needs, it is the supply of nitrogen that controls the yield of crops. The combined nitrogen in primary rocks has been estimated to be of the order of 10-12 μg/g. This converts to approximately 0.04 t/ha for a thickness of 15 cm at a bulk density of 2.63 g/cm, and is present as NH_4 within the structure of the silicate minerals. Under natural conditions, additions of nitrogen to the soil are through biological nitrogen fixation and through wet and dry deposition. The rates of addition are very variable but can be high.

The top 15 cm of many soil profiles in temperate regions usually contain between 0.1 and 0.3% chemically combined nitrogen. With an assumed bulk density of 1.3 g/cm^3, this represents between 2 and 6 tons of N per hectare. In contrast soils in arid regions often contain less than 0.1% N in the top 15 cm and may contain as little as 0.02% N.

Soderlund and Svensson (1976) and Jenkinson (1990) provide reviews of the global nitrogen cycle. The most important process for supplementing the nitrogen content of soils is biological fixation of dinitrogen by micro-organisms, which are of two types: those that are free living and those that fix dinitrogen symbiotically in root nodules. In some systems a clover or lucerne crop will increase the organic nitrogen in the soil by amounts in excess of 100 kg/ha.

The next most significant gain to the nitrogen pool is as ammonium and nitrate from the rain and dry deposition. In areas remote from industry the additions are normally less than 5 kg/ha/yr. Goulding and Poulton (1985) reviewed data from Rothamsted Experimental Station in Hertfordshire, United Kingdom. During the period 1888 to 1913 the inputs from the atmosphere were of the order of 4 to 5 kg/ha/yr, but by 1983 the rate of input had increased to approximately 20 kg/ha/yr. These data confirmed the trends presented by Jenkinson (1977) who noted an increase from 1889 to 1970, but not of the same magnitude; 1889-1903 4.4 kg N/ha/yr, 1960-1964 5.4 kg N/ha/yr, 1969-1970 8.6 kg N/ha/yr. Both groups suggested the increases probably arose from sources such as fuel combustion (chiefly fossil fuels) and NH_3 volatilization. These inputs may be of relatively minor importance on arable cropland when compared with other sources, but in forested ecosystems, pastures and extensively grazed rangelands the atmospheric inputs are of major importance. The principal forms of N in precipitation are NH_3, N oxides and organic N. The Central Water Planning

TABLE 3

Seasonal nitrogen inputs by precipitation in two upland catchments in Scotland

Site	Year	Season	Pptn (mm)	Nitrate-N (kg/ha)	Ammonium-N (kg/ha)
Glendyne	1984	Summer	127	0.40	0.89
	1984	Autumn	668	3.24	2.12
	1984	Winter	73	1.34	1.44
	1985	Spring	250	1.80	2.30
Peatfold	1984	Summer	139	0.28	0.48
	1984	Autumn	509	1.72	1.96
	1984	Winter	180	0.76	0.77
	1985	Spring	245	1.15	1.95

TABLE 4

Inputs of nitrogen from fertilizers, rain and N-fixation in grazed pasture systems in Australia and New Zealand

	Australia		New Zealand		
	Samford	Townsville	Woodville	Canterbury	Waikato
Mean annual Rf (mm)	1050	860	1400	771	160
Nitrogen inputs (kg/ha/yr)					
Fertilizers	374	0	0	0	0
Rain	4	4	3	10	3
N fixation		43	30	180	281
Total	378	47	33	190	284

Unit (1977) noted that for England and Wales in 1970 the relative inputs of N to the soil system were 1500 x 10^3 tonnes from fixation and rainfall, 1020 x 10^3 tonnes from animal and human wastes and 720 x 10^3 tonnes from fertilizer additions. Goulding (1990) noted distinct patterns in wet and dry deposition reporting that for Harwell in Oxfordshire, southern England, the wet deposition of N as NH_4^+ and NO_3^- was 5.9 and 3.2 kg/ha/yr respectively, dry deposition as particulate matter was reported as 1.7 kg/ha/yr for NO_3^- and as gaseous deposition at 12.8, 4.4 and 6.5 kg/ha/yr for NH_3, NO_2 and HN_3 respectively. Less complete records were reported for three further sites in southern England at Woburn, Rothamsted and Broom's Barn with approximately the same orders of magnitude of the wet and dry components of deposition.

There is considerable spatial variation in the amounts of N added to the soil from atmospheric inputs. For example in the USA the National Research Council reported distinct spatial patterns of N inputs, with < 5 kg N/ha/yr in western desert regions and levels in excess of 30 kg N/ha/yr close to stock feedlots in the Midwest (NRC, 1978). Peaks were also recorded near power generating plants and industrial centres. Jordan (1985), reporting data from tropical south America, noted N inputs from atmospheric sources with the range 5.0 to 10.0 kg/ha/yr. In addition to spatial variation, Hoeft *et al.* (1972) noted marked seasonal variability with a distinct peak in the spring in their study of atmospheric nitrogen inputs in

Wisconsin, USA. MacDonald *et al.* (1992) report a marked trend in atmospheric NO_3^- additions at eight sites along a transect from Minnesota, across Wisconsin and Michigan to Ohio. Wet deposition ranged from 8.78 kg/ha/yr in the west (Minnesota) to 24.56 kg/ha/yr in Ohio. There were similar trends in dry deposition, but the differences were greater, with 3.70 kg/ha/yr in Minnesota to 29.34 kg/ha/yr in Ohio. They reported variations in wet deposition of NH_4^+-N of 3.01 to 4.60 kg/ha/yr and 0.49 to 2.54 kg/ha/yr for dry deposition. There were distinct west to east trends from dry deposition, but no distinct patterns in respect of the wet deposition of NH_4^+-N. Edwards *et al.* (1985), reporting on the inputs and outputs of nitrogen in two catchments in upland Scotland, noted marked seasonality in the inputs of NO_3-N. Although the concentration in rainfall was lowest in the autumn during their period of study, the high amounts of precipitation during this period resulted in large inputs. The patterns with respect to NH_4-N were less distinct. Table 3 presents a summary of these data and also illustrates the contrast between the two catchments.

Ulrich (1990) reports a trend in increasing levels of nitrogen inputs to the soil system from the atmosphere through most of the 20th century, but notes recent changes which suggest a possible decline in levels of deposition as environmental legislation is introduced to control emissions.

In some systems the atmospheric additions of N may be of substantial importance in the overall nitrogen budget. This is shown by data for grazed pasture systems in New Zealand and Australia presented by Steele and Vallin (1988). These data (Table 4) show the atmospheric inputs to vary from approximately 1% of the total measured inputs of N to almost 10% of total measured inputs.

Stephenson and Raison (1988) similarly investigated the role of inputs of nitrogen from the atmosphere in a range of tropical food tree plants (Table 5)

The relative importance of the inputs of nitrogen in rain in the overall nitrogen budget ranges from a major component under cocoa to a relatively small contribution (1%) to total additions under coconut. Under natural conditions in the Amazon Basin, Salati *et al.* (1982) estimated the input of nitrogen by bulk precipitation to be of the order of 6 kg/ha/yr.

TABLE 5

Relative importance of nitrogen inputs from rain and fertilizers in tropical food tree plants (kg/ha/yr)

Crop	Rain	Fertilizer
Coconut	2	175
Oil palm	21	136
Cocoa	17	-
Coffee	10	300

In some agricultural systems water is added to the soil solely in the form of direct precipitation, in others direct precipitation inputs are supplemented with irrigation waters. Allison (1965) suggested that nitrogen addition through irrigation waters was likely to be negligible. This seems increasingly unlikely given the large amounts of nitrogen (chiefly nitrate) which are leached from soils into groundwaters. Steele and Vallin (1988) in their study of grazed pastures noted that losses of N due to leaching were of the order of 40 to 50% of the nitrogen additions at Canterbury and Waikato, and whilst no leaching loss was recorded at Woodville, losses in runoff were almost one third of the monitored additions. Barraclough *et al.* (1983) recorded N losses in leaching over three seasons under pasture with three contrasting nitrogen input levels (in the form of fertilizer). They recorded a minimum loss of 0.47 kg/ha/yr from an application rate of 250 kg N/ha/yr and a maximum loss of

155.8 kg/ha/yr from an application rate of 900 kg N/ha/yr. The ranges of losses from each of the three application rates were: 250 kg N/ha/yr - 0.47 to 6.3 kg/ha/yr; 500 kg N/ha/yr - 7.9 to 54 kg/ha/yr; 900 kg N/ha/yr - 144.1 to 155.8 kg/ha/yr. Global estimates for the amounts of N removed from agricultural lands in river waters suggest losses equivalent to 1 to 2 kg N/ha/yr.

Where there is a substantial leaching loss of NO_3^--N there will be an associated loss of cations such as Ca, Mg and K which may lead to acidification in upper soil layers. In tropical soil systems these losses in association with nitrate leaching from fertilized systems may have major impacts on the cation balance. This has been reported for the Amazon Basin in south America (Cahn *et al.*, 1983) and for southern Nigeria (Wong *et al.*, 1992). Similarly Omoti *et al.* (1983) reported leaching losses under oil palm in the main oil palm belt of Nigeria with 2000 to 3000 mm of rainfall on deep acid sandy soils. The annual losses of magnesium, calcium and chloride were reported as high to excessive and those of nitrogen, potassium and sulphur applied as fertilizer as moderate.

Where groundwater enriched by soil leaching is recycled as irrigation water the additions of N may be large. Lund *et al.* (1978) report data from the Santa Maria valley in California. Their estimate of nitrogen inputs from groundwaters was 126 kg/ha/yr. The magnitude of this input is not surprising when the nitrogen budget in this catchment is considered. Of the total inputs from fertilizers and groundwater of 679 kg/ha/yr, only 30% was utilized by crops, 37% was leached to groundwaters and 33% was unaccounted for. In this system the groundwater will continue to be a major source of N to irrigated crops and the input from irrigation water sources will increase if no change in agricultural practice is introduced. Similar conclusions of the importance of nitrogen sources from irrigation were reported in the USA by Saffigna *et al.* (1977) in the Midwest and by Meisinger (1976) in the east, both groups monitoring nitrogen fluxes in irrigated potatoes. In contrast Bingham *et al.* (1971) suggested that where the source of irrigation water was from surface water supplies the addition of nitrogen would be less than 3 kg/ha/yr in a watershed producing citrus products. The National Research Centre report of 1978 (NRC, 1978) suggested that with many river waters containing more than 2 mg of N per litre the contribution of N from surface irrigation water could easily be 20 to 40 kg N/ha/yr.

In a study of nitrogen budgets in sugar cane in the Chicama Valley in coastal Peru, Valdivia (1982) presented the following budget over an 18 month growing period:

Inputs:

a. Fertilizers	300 kg/ha
b. Root decomposition	139 kg/ha
c. Additions from irrigation	24 kg/ha
(River 20 kg/ha, well 32 kg/ha)	

Outputs:

a. Sugar harvested	147-172 kg/ha
b. Burning	63- 74 kg/ha
c. Leaching	33 kg/ha
d. Root uptake	235 kg/ha

This suggests a net loss of around 33 kg/ha, but because a large proportion of the fine roots is left in the soil after harvest, this will add a large quantity of mineralizable organic N to the soil. The systems will probably be in balance.

In a recent study in Iowa, Keeney and De Luca (1993) contrasted river nitrate levels in the Des Moines River catchment. Whilst there was no doubt that the high NO_3-N levels in the river (a mean of 5.6 mg/l NO_3-N 1980-1990) arose from intensive agricultural production in the catchment, it is suggested that the quality of the river water has probably been poor since farming began to dominate the land use in the late 1800s. Indications are that whilst fertilizer N use has increased over the period 1945-1990 there has not been a similar trend in the decline of soil water quality. A significant contribution to NO_3-N load of the catchment is the mineralization of soil-N coupled with subsurface tile drainage. Lucey and Goolsby (1993) report the results of monitoring the Raccoon River and Des Moines River noting considerable variation in NO_3-N levels on an annual and seasonal basis and in relation to antecedent moisture conditions and precipitation characteristics.

Whilst solute losses are a major component of nitrogen losses and by irrigation additions in many systems, evidence from the Loess Plateau in China shows that losses of nitrogen in these catchments are exceedingly high at 76.4 kg/ha in 1987 and 44.1 kg/ha in 1988; more significant is that 98% of this loss was associated with sediment rather than as solute load. These large sediment yields result from hyperconcentrated overland flow.

PHOSPHORUS

Most soils contain insufficient phosphate for good sustained yields of cultivated crops without the addition of P in some available form. When poor soils are first brought into cultivation phosphate is frequently the first plant nutrient which inhibits crop production. Deficiency of phosphate is widespread in the world, with particularly strong constraints on crop production in Australia, South America and southern Africa. Soils formed on alluvium and on some volcanic lavas frequently have adequate long-term supplies of P to sustain crop growth. Perhaps the most famous example of this is the Nile Valley where annual additions of sediment derived from the base rich rocks of the Ethiopian highlands sustained intensive crop production for millennia. Without this special case of annual replenishment, natural soils contain only very small amounts of P inherited from their parent material, and of this only a small amount may be used by crops.

As a plant nutrient phosphate differs from nitrogen in several respects. A major difference is the importance in natural systems of the amount of P provided from the parent material. A second difference is that, unlike nitrogen, phosphate ions are strongly adsorbed by the soil, or are precipitated as products with very low solubility, and as a consequence are rarely lost by leaching. There has been concern in recent times, however, about the possibility of loss of P by erosion of particulate matter with phosphates adsorbed to the soil mineral and organic fractions; additionally this may lead to the eutrophication of fresh waters. A further difference is that there is very little evidence for gaseous loss of phosphorus (as phosgene, PH_3).

The phosphate content of rocks has been reported to range from between 500 and 1400 μg P/g, with an average of about 100 to 1200 μg P/g. The phosphate content of soils was

TABLE 6
Dissolved and sediment P in fertilized plots (after Romkens and Nelson, 1974)

Fertilizer applied (kg P/ha)	Dissolved P (ppm)	P content of sediment (ppm)		
		Available (Bray No. 1 extraction)	Organic (by increase on ignition)	Total (by perchloric digestion)
0	0.07	14.6	152	558
56	0.24	35.4	99	446
113	0.44	57.6	106	461

reported by Wild (1988) to range from 134 μg P/g soil in a savannah soil from Ghana to 700 μg P/g soil in the United Kingdom.

The role of the atmosphere in the phosphorus cycle seems to be poorly understood. Since it does not exist in the form of stable gaseous compounds, phosphorus in the atmosphere is either adsorbed on to particulate matter (e.g. dust, including pollen) and exhaust fumes or dissolved in sea spray. The fallout of phosphorus, as dry deposition, has been estimated to be within the range of 3.6 to 9.2 Tg P per year for terrestrial ecosystems, 0.054 to 0.40 Tg P per year for freshwater ecosystems and 2.6 to 3.5 Tg P per year for marine ecosystems. This provides a total annual estimate of fallout from the atmosphere in the range of 6.3 to 12.8 Tg P per year (Pierrou, 1979). Bennett (1939) reported particulate additions of available P deposited from dust storms in Iowa, Michigan and New Hampshire ranging from less than 0.001 kg/ha/yr to 0.01 kg/ha/yr. In terms of the overall plant requirements these are exceedingly small additions. Jordan (1985) reviewing nutrient budgets in tropical South American ecosystems reported ranges of annual additions of P from 0.3 to 1.1 kg/ha/yr.

The movement of P through terrestrial systems in rivers has been estimated globally to be of the order of 1.9 to 3 Tg P annually (Sturm, 1973). This may be an underestimate, however, including only P in dissolved and particulate forms, probably excluding suspended materials. As referred to above there is considerable concern at present about the possible eutrophication of freshwater bodies because of the deposition of P adsorbed to solid particles eroded from the land. If the higher levels of these figures for atmospheric deposition and flowing water are taken as correct, they broadly match the estimates of P deposited in the oceans, given as 13 Tg P annually by Emery *et al.* (1955).

The concentrations of soluble P in stream waters were shown by Thomas and Crutchfield (1974) to be between 0.01 and 0.05 ppm in sample taken from streams draining agricultural watersheds on sandstone and shale rocks in central and west Kentucky. In this study streams draining the most intensively cultivated watersheds carried concentrations less than 0.03 ppm. Levels ranging from 0.30 to 0.35 ppm were found in waters draining areas of high phosphate limestone rocks. Thomas and Crutchfield compared their data with results from a study undertaken 50 years earlier, and showed no significant increase in stream concentration of soluble P although there had been a 9 to 10-fold increase in the use of P fertilizers. Ryden *et al.* (1973), however, warned against the comparison of concentrations of P in stream waters and artificial drains, particularly below fertilized fields. They noted that artificial drains increase rates of infiltration, and percolation reduces the residence time of the water during which phosphate adsorption takes place, increases the downward movement of organic matter and produces sediment. Duxbury and Peverly (1978) and Miller (1979) have illustrated the importance of organic matter in accelerating the downward movement of P, particularly in highly organic soils.

Losses as surface runoff show considerable variability in both natural and agricultural systems. Timmons and Holt (1977) presented results from a 5-year study of nutrient losses in surface runoff from a native prairie. They noted the annual weighted ortho-P concentrations were 0.18 ppm and organic -P concentrations were almost twice this figure. The overall losses ranged up to 0.25 kg P/ha depending upon the amounts and pattern of precipitation. In an earlier study (Timmons and Holt, 1970) they had reported losses equivalent to 0.65 kg/ha of soluble P in one leaching of a frozen alfalfa plot. Eighty percent of this was inorganic P.

When erosion occurs, soil moving to lake and stream water carries adsorbed P with it. It has been widely reported that the total P carried by sediments is much larger than that in solution. Data on sediment and runoff from studies in a range of catchments show that ratios of total P/solution P can exceed 200 to 400 when large amounts of sediment are present, although values of 50 to 100 are more common (Burwell *et al.*, 1975; Hanway and Laflen, 1974; White and Williamson, 1973).

When plots are fertilized there is normally an increase in the concentration of P in both runoff water and sediments. Romkens and Nelson (1974) show a proportionate increase in the amount of soluble and available P in direct proportion to the fertilizer added. These data are illustrated in Table 6.

Vaidiyanathan and Correl (1992) noted the P loss from contrasting forested and agricultural watershed. The recorded Total P loss was 0.31 kg P/ha/yr from the forest and 2.41 kg P/ha/yr from an agricultural catchment. Of this the proportions of particulate and dissolved were 77:23 for the forest and 95:5 for the agricultural catchment, the inorganic particulate P being particularly significant in this latter catchment. In addition to these differences they noted significant variations in P export in relation to river discharge.

SULPHUR

Sulphur is essential to plants, the amounts needed being similar to the amounts of phosphorus required, ranging from 15 to 50 kg S/ha/yr. Sulphur deficiency in crops has been recorded in most parts of the world, except coastal regions which receive sulphur in sea spray, and those close to urban and industrial centres which receive sulphur from the atmosphere (Tisdale *et al.*, 1986). Because of reductions in the emissions of SO_2 into the atmosphere from fossil fuels since the mid 1970s (a trend which will continue in most industrialized nations as environmental targets for SO_2 emissions require even further reductions than have been achieved to date), and the increasing use of fertilizers low in sulphur, the occurrence of deficiencies seems likely to increase.

The atmosphere is a major source of S for plant growth (Paricha and Fox, 1993). The atmosphere contains sulphur compounds both as gases, of which sulphur dioxide is the dominant one, and in particulate form as sulphates. Particulate sulphates near the coast will contain sodium and other inorganic sulphates, near urban and industrial centres, the aerosol containing sulphate is likely to be ammonium sulphate, but also free acid emitted on the combustion of sulphur bearing fuels. Lindbergh *et al.* (1986) and Shepherd *et al.* (1989) have estimated the sulphur contribution from dry deposition (including particulate and gaseous forms) is greatest for those sites near sources of sulphur emission, with at least 62% of total sulphur deposition occurring as dry deposition. During the last 100 years levels of sulphur deposition in rainfall at Rothamsted Experimental Station in Hertfordshire have increased from 7.8 kg/ha/yr in the period 1881-1887 to 20.6 kg/ha/yr in the period 1969-73, and in the early 1980s levels of 25-35 kg/ha/yr were recorded (Goulding and Poulton, 1985). There appears to be substantial variation across the globe. Whitehead (1964) reported sulphur additions in rainfall for sites in a number of countries (Table 7).

Olson and Rehm (1986) present a similar summary of data for the USA and Canada, some of which is more recent. Nevertheless the range of inputs and the patterns of variation are broadly similar.

TABLE 7
Sulphur additions in rainfall (kg/ha/yr)

England	
Godalming (Surrey)	32
Portishead (Coastal)	16
St. Helens (Industrial)	83
Scotland	
Loch Katrine	13
Germany	
Rural	13
Industrial	90
Sweden	
Rural	2-10
Industrial	47
USA	
Michigan	9-13
Indiana (Industrial)	142
Florida	6
Australia	
Victoria (Coastal)	3-8
(Inland)	<2
Western Australia	1
New Zealand	
Rural	0.3-3
Industrial	9

Bromfield *et al.* (1980) monitored monthly rainfall at 10 locations in Kenya during 1977 and 1978, recording amounts deposited from 1.58 to 3.81 kg S/ha/yr with a mean of 3.47. Bromfield (1974) also recorded annual inputs of sulphur of 1.14 kg/ha/yr in south Nigeria. There has been recent concern about sulphur additions through biomass burning, particularly in forested regions. Andreae and Jaeschke (1992) have produced a recent estimate based on observations over Amazonia of 2.8 Tg S/a. This estimate is considerably lower than earlier estimates, but is based on a better data set and consequently is probably more reliable. Whilst this input is relatively small in comparison to the areal sulphur budget on a global scale, as biomass burning occurs predominantly in tropical regions during a defined burning season, it may be the dominant sulphur source in remote tropical regions during a significant part of the year. In the southern states of the USA, Suarez and Jones (1982) identified the inputs of sulphur as: rainfall 10.7 kg/ha/yr, air deposition 1.8 kg/ha/yr and particulate matter 3.0 kg/ha/yr. Tamm (1958) and Eriksson (1966) provide estimates for the magnitude of wet and dry deposition for four cities in northern Europe (Table 8)

TABLE 8
Wet and dry deposition of sulphur from the atmosphere for four northern European cities (kg S/ha/yr)

	Wet	Dry	Total
Stockholm	4.5	6	11
Hamburg	14.6	60	75
London	11.1	67	78
Paris	7.5	33	41

Dry deposition is believed to be mainly as SO_2 and to a much lesser extent as particulate sulphate. The amount of dry deposition depends upon the nature of the surface exposed to the air and on the concentration of sulphur compounds in the air. The average total S deposition in Britain has been estimated as 70 kg/ha/yr of which 20 and 50 kg/ha/yr are from wet and dry deposition respectively (DOE, Central Unit on Environmental Pollution, 1976). Andreae and Jaeschke (1992) reviewed wet deposition fluxes in tropical regions, primarily areas of rainforest and moist savannah. Wet sulphur fluxes ranged from 0.7 to 6.8 kg S/ha/yr with a median value of 1.7 kg S/ha/yr. These figures broadly correspond to the estimates presented by Galloway (1985) of 2 kg S/ha/yr for wet deposition in remote continental areas. In these systems atmospheric deposition is often a major external source of sulphur input in to the system. MacDonald *et al.* (1992) report trends in wet and dry sulphur deposition in the Great Lakes region of the USA, noting variations in levels of wet and dry deposition from 9.69 and 2.60 kg/ha/yr in Minnesota and 36.55 and 18.81 kg/ha/yr in Ohio. It will be noted that there is a marked contrast between the rates of deposition in remote, under populated areas often with low levels of industrial activity and the more densely populated and in places more industrialized areas of the USA.

The sulphur levels in waters which might be used for irrigation show marked patterns downstream, depending on the contributions from geologic formations and agricultural, urban and industrial sources. For example the Yakima River in Washington State was reported as containing sulphur levels of only 0.7 mg/l in its upper reaches, but this increased to 1.4 mg/l in its middle reaches to 5.1 mg/l at its mouth. Yoshida and Choudhry (1972) observed in the Philippines that irrigation waters contained 27 mg S/l and this was sufficient to meet the sulphur requirements of the rice crop. They reported that in general levels of 4 to 6 mg/l were common in irrigation waters and this was sufficient for the needs of most crops. In contrast Ismunadji and Zulkarnaina (1978) report contents of sulphur in irrigation waters in Indonesia with ranges of 1.28 to 20.2 mg SO_4-S/l, with 7 of their 9 samples having concentrations at 6.17 mg SO_4-S/l or less. They suggest that these levels are insufficient to meet the sulphur demands of lowland rice. Blair *et al.* (1979) observed S deficiencies in South Sulawesi, Indonesia, in rice paddies supplied with irrigation water containing 2.8 mg S/l. In contrast Olson and Rehm (1986) report concentrations of 30 to 250 mg S/l in irrigation water from groundwater sources in South Dakota and a range of 3 to 503 mg S/l in irrigation waters in northwestern Kansas.

There is very little information available for sulphur needs in groundwaters used for irrigation. Cheema and Arora (1984) report the mean concentration of groundwaters used for irrigation to be approximately 8 mg S/l, which during a typical season would provide 24 kg S/ha to a wheat crop. They commented that in years of higher than average rainfall when irrigation requirements were lower, many of the crops showed signs of sulphur deficiency.

Information on nutrient supplies of S in sediments is rare, but Lipman and Congleave (1936) estimated that on average for the USA 6.7 kg S/ha/yr are lost from topsoils by erosion and this sediment will be a source of nutrients further down the catchment. Vancells and Cros (1978) suggested S lost in sediments in Spain was an important loss in the overall sulphur budget of the system.

OTHER NUTRIENTS

The three nutrients considered above have been the focus of the bulk of the research and data collection to date, but there has been a series of studies for particular countries or regions

TABLE 9

Atmospheric inputs for a range of nutrients from studies in Sweden[1], Norway[2], Malaysia[3], the Northern Territory of Australia[4] and Ghana[5]

Nutrient	Sweden	Norway	Malaysia	Australia	Ghana
			kg/ha/yr		
Na	4-30	0.8-6	nd	1.1	nd
Cl	2.5-40	1-257	nd	1.6-1.8	nd
Ca	6-19	3-14	34	nd	12
K	1.1-3.5	0.8-8	11	0.3	18
NH_3-N	0.7-4.0	)0.8-6	)20	0.7	)15
NO_3-N	0.15-8.0	)	)	0.5-0.8	)
S	nd	3-19	nd	nd	nd
Mg	nd	0.4-17	3	0.2	11
P	nd	nd	0.2	nd	0.4

[1] Emanuelsson *et al.* (1954).
[2] Lag (1963).
[3] Shorrocks (1965a and b).
[4] Wetselaar and Hutton (1963).
[5] Nye and Greenland (1960).

TABLE 10

Atmospheric additions of available plant nutrients as dust in three States during dust storms in 1937 (kg/ha/yr)

Plant nutrient	Iowa	Michigan	New Hampshire
K_2O	0.18-0.26	0.09-0.13	0.07-0.10
CaO	0.03-0.32	0.02-0.16	0.01-0.13
MgO	0.01-0.14	0.005-0.07	0.004-0.06
Fe_2O_3	0.08-0.42	0.04-0.21	0.03-0.17
MnO	0.002-0.01	0.001-0.005	<0.001-0.004

which have attempted broad summaries of the inputs from precipitation. These are listed in Table 9. These data illustrate the complex pattern of variability in the input through precipitation of a range of nutrient ions. The higher levels of chloride and sodium in the Scandinavian studies were generally found to be associated with coastal areas, and the higher levels of potassium in these studies were frequently explained by sources such as coastal inputs and the burning of fuel. The inputs in Malaysia were associated with rainfall inputs in excess of 2500 mm. MacDonald *et al.* (1992) report regional variations in the USA in ionic deposition at eight sites in the Great Lakes region with ranges for Mg^{++} from 0.29 to 0.74 kg/ha/yr wet deposition and 0.09 to 0.45 kg/ha/yr dry deposition; Ca^{++} 1.60 to 2.95 kg/ha/yr wet deposition and 0.32 to 1.23 kg/ha/yr dry deposition; K^{+} 0.16 to 0.91 kg/ha/yr wet deposition and 1.31 to 8.52 kg/ha/yr dry deposition. Whilst there are spatial trends in these data they are far less distinctive than for S and N deposition.

Information on additions to the soil through the deposition of dust is exceedingly scarce. Some data are presented by Bennett (1939)in his major study of soil erosion and conservation. Table 10 lists the available plant nutrients deposited as dust during storms in 1937 in Iowa, Michigan and New Hampshire. These contributions are exceptionally low, but there is little information with which to compare these data.

CONCLUSIONS

In conclusion it is apparent that the plant nutrient inputs in to the soil-plant system by rain, dust and irrigation waters are very variable across the globe. There is exceptionally sparse information on the contribution of nutrients to this system from sedimentation sources. The variability in the first group of possible sources is substantial both in time and space. For example, with respect to atmospheric inputs there is frequently substantial variation in relation to the nearness to industrial and urban centres and also for a number of the nutrients with respect to closeness to marine zones. In addition there is substantial variability in time both in short time periods and over seasons. The work of Edwards *et al.* (1985) illustrates this for nitrogen inputs in two upland Scottish catchments. In this study the peak rainfall inputs coincided with the lowest concentration of nitrogen in the rainfall, but when the concentrations and rainfall amounts were combined the period of largest precipitation input was also characterized by the greatest nitrogen input in to the system. This illustrates the need to pay particular attention to the nature and patterns of variability.

The importance of these sources of nutrients to overall nutrient budgets also shows substantial variability. In low external input systems (where external inputs equate with inorganic and organic fertilizer additions) the inputs from these sources may contribute a substantial part of the overall nutrient budget. The relative contribution of nitrogen from these sources reduces when the cropping system includes plants capable of fixing atmospheric nitrogen. In systems where fertilizers are applied, either as inorganic or organic materials, the contribution of these sources may become less important, at least with respect to the major nutrients; there may however be an important role for the inputs of minor or trace nutrients from these sources. With reference to the plant requirements for sulphur, the role of the inputs from atmospheric sources is often a significant contribution to overall plant requirements. With the decreases in the emissions of sulphur from power generating plants and the reduction in sulphur as 'impurities' in fertilizers, it is possible that in the future sulphur deficiency may become more widespread in areas where it has not been recognized because of these contributions.

In undertaking this review it became apparent that there is a paucity of quality data relating to inputs of nutrients from atmospheric sources, irrigation waters and sedimentation. In particular information on sedimentation is non-existent, and the description of the quality of sources of irrigation waters tends to be concerned with the salinity or sodicity of these waters and their potential damaging effects rather than the possible nutrient additions through these waters. As shown in the study in the Santa Maria Valley in California (Lund *et al.*, 1978) where the source of irrigation waters for crop production is near surface groundwaters, the leachate from these crop production areas may be a substantial part of the groundwater recharge. As a consequence, in systems where a substantial proportion of the applied nutrients is 'lost' out of the soil system to groundwaters there may be substantial pools of nutrients in the groundwaters, which will be applied in irrigation waters. There is a need to characterize the nature of irrigation waters more fully and to account for the nutrients added in these waters in the overall nutrient budget for the system.

In lower input agricultural systems the plant nutrient inputs from non-fertilizer, non-soil and non-nitrogen fixing sources, will increasingly become large components of the overall plant nutrient budgets. If appropriate strategies for the management of the plant nutrients within these systems are to be planned and developed, it is essential that more complete information be available about the nature and magnitude of these sources.

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Contribution of soil reserves to plant nutrient supply

The concept of a 'reserve' is well understood and commonly used in mining terminology. A reserve denotes a deposit for which information on thickness and extent (obtained for example by drilling) is available, and for which a reasonable knowledge of tonnage exists. A reserve can usually be mined and processed today at a profit. This implies that there is adequate information on the geologic structure and on chemical and mineralogical characteristics to develop and implement mining and beneficiation plans, respectively.

By analogy with mining terminology and in the context of nutrient supply to plants, 'soil reserves' can be thought of as mineral forms of nutrients which have been inherited from the soil parent material and about which there is a reasonable understanding. Such minerals are usually of primary origin when derived from a parent rock, but may also be secondary if inherited from weathered deposits or contributed by aeolian deposition.

Within the scope of this paper it is not possible to consider all nutrients which are essential for the growth of plants. Instead, two contrasting major nutrients – phosphorus (P) and potassium (K) – have been singled out for consideration. Because they have different ionic forms, namely an anion and a cation, respectively, their reactions in soils are quite different with respect to concentration in the soil solution and to some extent, the mechanisms involved in their supply to plant roots.

This paper considers the occurrence and weathering of primary forms of P and K in soils and the mechanisms involved in their supply to plants.

NATURE OF SOIL RESERVES

Primary forms

Phosphorus

Minerals of the apatite group are calcium phosphates which vary in composition and are by far the most abundant primary source of P in rocks, soil parent materials and soils. Igneous apatites are usually coarsely crystalline and have a chemical composition close to that of fluorapatite ($Ca_{10}(PO_4)_6F_2$), which has a very low solubility in water, except under strongly

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PAPER 3.3

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acid conditions. Carbonate substitution for phosphate in the apatite structure commonly occurs (Lehr and McClellan, 1972) and this causes a decrease in crystallite size and an increase in specific surface area (McClellan and Lehr, 1969). Carbonate substitution determines the chemical reactivity of an apatite. Not only can this be quantified, but it also has a sound theoretical basis (Hammond *et al.*, 1986). The rate and extent of dissolution of apatite in soils are determined by characteristics of the apatite, namely chemical and mineralogical composition, particle size, and soil and environmental factors, as discussed below.

Potassium

There are two major primary sources of K in rocks, soil parent materials, and soils; these are K-bearing micas and K-bearing feldspars (Rich, 1968). The K-bearing mica structure consists of negatively-charged, 2:1 layers that are bound together by interlayer cations, mainly the K^+ ion (Sparks and Huang, 1985). The 2:1 layer is composed of an octahedral sheet between two sheets of tetrahedra. Micas are classified into two major groups - dioctahedral, where two out of three octahedral positions are occupied, and triocatahedral, where all three octahedral positions are filled (Rich, 1968). The end-member micas are: dioctahedral muscovite - $KAl_2\ (AlSi_3)O_{10}(OH)_2$ and trioctahedral biotite - $K(Mg,Fe)_3(AlSi_3)O_{10}(OH)_2$.

Micas are common components of granitic and acidic rocks, with biotite and muscovite being the most extensive micas in igneous and metamorphic rocks. Micas are generally more prevalent in weakly-weathered soils. In soils which have undergone much weathering, triocatahedral micas are uncommon (Sparks and Huang, 1985). As a consequence, the micas in most weathered soils are predominantly dioctahedral. Interstratification with hydroxy alumina appears to increase the persistence of dioctahedral micas.

The ideal composition of K feldspar is $KAlSi_3O_8$ (Jackson, 1964) but this rarely occurs in nature (Sparks and Huang, 1985). The K feldspars are abundant in igneous, metamorphic and sedimentary rocks, accounting for approximately 15% of the total lithosphere (Ahrens, 1965). In strongly-weathered soils, K feldspars are present in small quantities or are absent (Sparks and Huang, 1985).

Both K-micas and K-feldspars constitute important reserves of K in soils but weathering reactions, primarily involving dissolution, are required for the release of K.

Weathering processes

Physical, chemical and biological processes can be involved in the weathering of minerals. Of these, chemical weathering is the most important. Water is essential because it is required both for dissolution to occur and for removal of the soluble products of decomposition. Several processes are involved in chemical weathering and they are often grouped together as hydrolysis, hydration and oxidation (Nortcliff, 1988). Because of their low solubility, the long equilibration times required, and the general complex nature of many soil minerals (Kittrick, 1977), understanding of mineral dissolution rates and stabilities is not well advanced. This applies to the primary mineral forms of P and K. In this section, major attention will be directed towards the dissolution process.

Phosphorus

The soil properties which influence the dissolution of apatite may be seen from the following equation for fluorapatite:

$$Ca_{10}(PO_4)_6F_2 + 12H^+ \rightarrow 10Ca^{2+} + 6H_2PO_4^- + 2F^-$$

An adequate supply of moisture and protons (H^+), and any factor which decreases the solution concentration of Ca and P, will favour dissolution. Thus the following soil-related factors are likely to be important for dissolution, in addition to soil moisture:

- The concentration of H^+ in the soil solution and the pH-buffering capacity (proton supply).
- The concentration of Ca in the soil solution and the Ca-buffering capacity (Ca status).
- The concentration of P in the soil solution and the P-buffering capacity of the soil (P status).

Although it is generally believed that soil acidity, or proton supply, is the single most important factor influencing the dissolution of apatite in phosphate rock materials added to soil (Peaslee *et al.*, 1962), recent work by Robinson and Syers (1990) indicated that, in the absence of a sink for Ca, pH has little effect on dissolution. Subsequent work by Robinson *et al.* (1992) indicated that, in acid soils which could supply sufficient H^+ to achieve complete dissolution of the carbonate apatite present in Gafsa phosphate rock, the amount dissolved was little influenced by pH. It seems likely that protons are primarily required to disrupt chemical bonds at the apatite surface (Chien, 1978); pH-buffering capacity is probably a better predictor of dissolution than is pH, *per se* (Kanabo and Gilkes, 1987).

According to the solubility product principle, the provision in a soil of a sink for both Ca and P is essential for the continued dissolution of an apatite. This occurs because of the lowering of the solution Ca and P concentrations. The soil sink for Ca is provided by the cation-exchange capacity (CEC) of the soil, enabling the Ca which dissociates from the apatite surface to become part of the exchange complex (Khasawneh and Doll, 1978). The affinity of a soil for Ca is high when percent Ca saturation is low, which is usually the case when overall base saturation and soil pH are also low. This condition is common in acid soils, thus favouring apatite dissolution. In contrast, when the exchange complex is largely saturated with Ca, the affinity of the soil for Ca is low. This explains why apatite dissolution is negligible in soils with neutral or alkaline pH values.

Soil P status plays a role in apatite dissolution similar to that of Ca, although its effect appears to be less pronounced. The higher the P status of a soil, the higher the P concentration in the soil solution, and the lower the rate and extent of apatite dissolution. If the soil solution is saturated with respect to the solubility product of apatite, dissolution will cease. Experimental evidence suggests that the P-retention capacity of a soil has a significant effect on apatite dissolution, increasing with an increase in P-retention capacity because of a progressive decrease in solution P concentration (Smyth and Sanchez, 1982).

In removing Ca and P from the soil solution by root uptake, plants can promote the dissolution of apatite. The effect is accentuated if roots are acidifying the rhizosphere (Nye and Kirk, 1987). Acidification of the rhizosphere is enhanced when plants are supplied with nitrate nitrogen and are P deficient (Hedley *et al.*, 1983).

TABLE 1

Changes in total P (P_T) and apatite P (P_A), as assessed by acid-extractable P in an inorganic P fractionation scheme, with time in a chronosequence of soils developed from wind-blown sand in New Zealand (data of Syers and Walker, 1969). Results in mg P/kg.

Years	0		50		500		3000		10 000	
Horizon	P_T	P_A	P_T	P_A	P_T	P_A	P_T	P_A	P_T	P_A
1	347	187	468	178	620	164	408	37	584	0
2			389	222	489	183	343	29	311	0
3			386	216	367	186	324	104	257	12
4			347	197	391	224	317	132	120	0
5			366	196	374	224	319	139	211	12

Potassium

It is reasonably well established that K-bearing micas release K^+ as a consequence of (i) transformation to expansible layer silicates by exchanging the K^+ with hydrated cations and (ii) dissolution of the micas followed by the formation of weathering products (Sparks and Huang, 1985). The former process is thought to occur by weathering at edges (Mortland, 1958) and by weathering of layers (Jackson *et al.*, 1952). The expanded interlayers formed are believed to create 'wedge zones' (Jackson, 1963), because of internal termination of the expanded interlayers. These wedge zones are able selectively to retain K^+, contributing to K fixation. According to Huang *et al.* (1968) the mechanisms involved in the release of K^+ from micas by dissolution are more complex than those involved in a simple transformation of micas to 2:1 expansible layer silicates.

Sparks and Huang (1985) described a number of factors which influence the release of K^+ from micas. These include structural characteristics, including tetrahedral rotation and tilting, and hydroxyl orientation; chemical composition; particle size; structural imperfections; extent of K depletion; layer charge alterations; hydronium and other inorganic cations; organic anions, and wetting and drying. It can be seen from this list that K release from micas is a complex process, being influenced by a wide range of factors.

The mechanisms involved in the release of K^+ from the weathering of K-bearing feldspars are not well understood, although some of the factors which influence K^+ release have been established with some reliability. Sparks and Huang (1985) list structural properties, particularly the inclusion of Na in the structure and the degree of disorder of the Al and Si distribution, hydronium ions, which cause initial weathering and weaken the feldspar structure, and the complexing effect of organic acids as being the most important. Organic acids are important as a source of protons and as complexing agents.

For comparable particle sizes, K-feldspars weather more rapidly than micas, and biotite weathers more rapidly than muscovite. Weathering reduces both the amount and particle size of K minerals. In weakly-weathered soils, K minerals remain in the sand and silt fractions but as weathering and leaching progress the K content of all fractions becomes low (Wild, 1988b).

Amounts

Phosphorus

The average P content of rocks is between 1000 and 1200 mg P/kg (Wild, 1988a) and a very high proportion of this is likely to be apatite. The total P content of soils ranges from about 200 to 5000 mg P/kg, with an average of approximately 500 mg P/kg (Barber, 1984). If there is an adequate supply of moisture and protons for initial disruption of the surface, apatite dissolves during soil formation and the P released is converted to secondary inorganic (Fe- and Al-bound P) and organic P (Walker and Syers, 1976). If the apatite is present as inclusions within other minerals (Syers *et al.*, 1967) it is likely to be pedogenetically inert over long periods of time, depending on the stability of the host mineral.

Information on the rates of weathering of apatite in soils has been obtained using chemical fractionation procedures. Such procedures are empirical but they can provide useful information. In chronosequence studies in New Zealand, apatite declined with increasing time, more rapidly in surface horizons than in lower horizons, reflecting the higher degree of weathering in surface horizons (Walker and Syers, 1976). The amount of apatite approached zero after several thousand years in the surface horizons and in the lower horizons somewhat later. In a soil sequence developed from greywacke and mica schist in a high rainfall (5090 mm per annum) area, apatite as assessed by acid-extractable P had completely disappeared from the profile by 22 000 years. In a sequence of soils developed on slightly preweathered wind-blown sand dominated by quartz and feldspar under an annual rainfall of 850 mm, apatite decreased to essentially zero after only 10 000 years (Table 1).

Potassium

The total K content of rocks varies considerably but according to Wild (1988) average values are approximately 1 to 2%. For soils, reported total K values range from less than 0.01 to approximately 4% (Wild, 1988b). There is little quantitative information on the rate of weathering of micas and feldspars in soils, in contrast to the situation for apatite. The K released into solution by weathering can be retained as exchangeable K, which has a high potential availability to plants, or it can be fixed by vermiculitic minerals, if present, as slowly-exchangeable K (Sparks and Huang, 1985). The inter-relationships between the forms of K in soil are shown in Figure 1.

This schematic diagram emphasizes the potential importance of soil reserves of K but the question of the rate of supply to the soil solution remains.

MECHANISMS OF NUTRIENT SUPPLY

The uptake of nutrients by plant roots is determined by the ion absorption characteristics of the root and by supply characteristics of the soil (Barber, 1984). Mechanisms of supply are often considered in terms of:

- root interception,
- mass flow,
- diffusion.

FIGURE 1
Inter-relationships between the forms of potassium and their approximate amounts for twenty English topsoils (from Wild, 1988b)

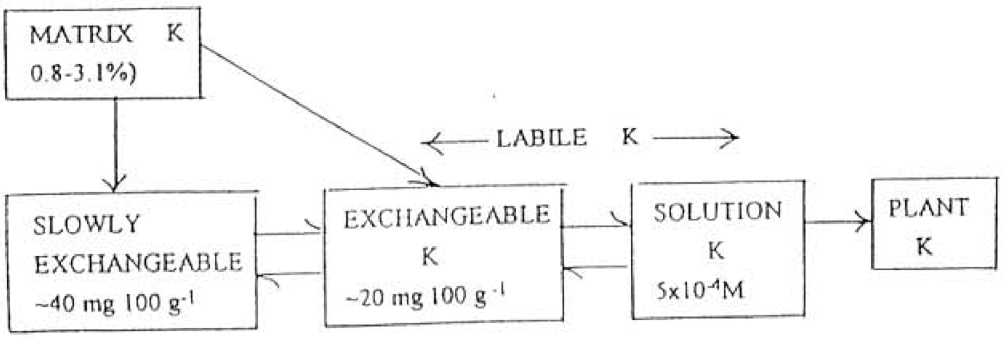

TABLE 2
Relative significance of root interception, mass flow, and diffusion in supplying N, P, and K to maize growing in a fertile Alfisol (taken from Barber, 1984)

Nutrient	Amount required (kg/ha)	Relative significance (%) of		
		Root interception	Mass flow	Diffusion
N	190	2	150	38
P	40	1	2	37
K	195	4	35	156

Root interception

Root interception is unlikely to be an important mechanism of P and K supply in soils because the volume occupied by roots is usually a very small proportion of the soil's volume. Root volumes in the top 20 cm of soil vary in the range of 0.4% for maize (Mengel and Barber, 1974) to 2.8% for some grass species (Dittmer, 1940), with an average value of less than 1% (Barber, 1984). This implies that less than 1% of available P and K can be supplied by root interception and that other mechanisms are involved if plants are to obtain an adequate nutrient supply.

Mass flow

Mass flow describes the movement of ions through the soil to the root surface in the convective flow of water caused by water absorption by the plant (Nye and Tinker, 1977). The plant transpiration stream acts as a pump, drawing soil water and ions present in the soil solution to the root surface. For ions which are weakly adsorbed by soil components (such as NO_3^- and SO_4^{2-}) and are present in the soil solution in relatively large concentrations, transportation by mass flow is the dominant mechanism of supply. By multiplying water use by the plant by the concentration of a particular ion in the soil solution the amount of that nutrient supplied by mass flow can be calculated. These can be compared with plant requirements. Values for maize are shown in Table 2.

These results indicate that mass flow supplies only a very small proportion (5%) of plant P requirement but a higher proportion (approximately 18%) of plant K requirement.

Diffusion

When mass flow is not sufficient to meet the demand of the plant for a particular nutrient, because the concentration of that nutrient in the soil solution is too low, the concentration in the soil at the root surface is decreased. This causes a concentration gradient, along which ions diffuse. Ions which are strongly retained in soil, particularly $H_2PO_4^-$, are present in very low concentrations in the soil solution (commonly 10^{-5} M and lower in P-deficient soils) and are transported by diffusion; ions such as K^+ which are less-strongly held than $H_2PO_4^-$ and are present in higher concentrations in the soil solution (10^{-3} to 10^{-4} M for K^+) are still transported primarily by diffusion (Table 2) but mass flow contributes to a significant extent.

The use of radio-isotopes, in conjunction with autoradiography, has produced very useful visual models of nutrient transport to plant roots, particularly with regard to the distance over which transport occurs. For example, it has been shown that $H_2PO_4^-$ does not usually diffuse over distances greater than 0.2 mm (Sanders, 1971). Also, using Rb as a label for K, Walker and Barber (1962) were able to demonstrate depletion of ^{86}Rb around maize roots, confirming the importance of a diffusion mechanism for Rb supply and by inference K supply.

BALANCE BETWEEN SUPPLY AND REQUIREMENTS

Soil reserves of P and K are determined primarily by the soil parent material and the minerals it contains, and by the degree of weathering of the soil. Crop requirements for P and K vary with the species and variety, and with the yield achieved. In natural ecosystems where nutrient cycles are 'tight' and where nutrient removal is very low, and also in extensive agricultural systems where nutrient offtakes are also low because of low yield, the rate and extent of supply of P and K from soil reserves are likely to be sufficient to meet plant requirements, at least in weakly-weathered soils. The fact that P and K responses are commonly obtained in more-intensive agricultural systems indicates that the supply from soil reserves is insufficient to meet crop requirements. This is particularly the case for more highly-weathered soils where reserves have largely been depleted. For a given species, crop yield determines crop demand. The heavy use of fertilizer N can dramatically increase requirements for K, in particular.

The situation for K in China is worthy of brief comment. In the northern part of China, weak to moderate weathering of recent parent materials (loess and alluvium) results in the common occurrence of dominant micaceous minerals and usually a high K-supplying power (Xie, 1985). Only on sandy soils and soils which have been cropped intensively are K responses obtained (Xie and Hasegawa, 1985). In contrast, in the tropical and subtropical southern part of China, kaolinite is the dominant clay mineral and soil K reserves are low or very low, with a result that responses to K are now very frequently obtained. This has not always been the case. Even in the southern part of China, crops showed little or no evidence of K deficiency in the 1950s (Xie and Hasegawa, 1985). With more intensive cropping and increasing application of N and P fertilizers, increasingly large responses to fertilizer K were obtained in the 1970s. Now almost all parts of China have became seriously K deficient (Xie and Lu, 1988).

With the anticipated move towards more intensive agriculture in the developing world, there will be an increasing need for fertilizer P and K. It is in the soils of subtropical and tropical regions that soil nutrient reserves are the lowest and where the need for more fertilizers will be the greatest.

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Transfer of plant nutrients and management of organic sources in China

China is an agricultural country. Recently it has ensured the living of a 1.17 thousand million population. In 1991 Chinese farmers produced cereals in the amount of 440 million tons, cotton 5.67 million tons, rough material of sugar and oil nearly 100 million tons. On average production per person per year reached 387 kg cereals, 4.9 kg cotton, 14.3 oil material, 73.7 kg sugar material, 27.5 kg meat and 11.8 kg fish.

These data show the importance of supplying the soil with more plant nutrients. These plant nutrients come from fertilization. Through crop growth and harvest they are converted into food and clothes for use by human beings. About 60-70% of the produce are directly used by people, 30-40% are used as feed by animals. Finally, all these nutrients change into wastes. Of all these wastes only about 70% can be transferred into cropped areas. About 30% of the wastes are lost, some disposed of in landfills in sub-urban areas, some into rivers or other water systems. Today these wastes have already become the most serious source of pollution. Hence nutrient transfer is not only a plant nutrient problem, it is also a very serious environmental and ecological issue.

Chemical fertilizer application is the most important factor of nutrient transfer from non-cropped to cropped land in China. Total consumption was nearly 30 million tons pure nutrients in 1992. About 21 million tons are produced in the country. Imports amounted to 9 million tons. The production and application of chemical fertilizers increase by about 5% each year. Organic matter resources, in the order of 3 thousand million tons, have been used in 1991 with a content of plant nutrients of nearly 36 million tons NPK. However, these organic sources cannot be used completely because of a loss of about 20-30%. Thus, in China, plant nutrients are provided for 50% by chemical fertilizers, while the other 50% come from organic manure.

The transfer of plant nutrients from non-cropped to cropped areas is quite difficult, because their efficiency is lower than that of chemical fertilizer. The application of organic sources of nutrients also requires a considerable input of labour. However, some farmers have developed techniques which are adapted to local environments. Furthermore, some local governments provide some financial support. A distinction needs to be made between different farming systems:

PAPER 3.4

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- agriculture-forest system;
- agriculture-animal system;
- agriculture-fish system;
- combinations of the above.

All the forest, animal, fish and human wastes are transferred into the cropped system by manual labour or by small cart or tractor. These practices imply that the transportation radius cannot expand beyond a few kilometres. In order to save transportation costs it is now recommended that crop residues be returned to the cropped soil which requires only simple equipment and is a very useful technique to increase soil organic matter and soil fertility.

The transfer of plant nutrients also includes crop-tree intercropping, fruit-grass intercropping, livestock and poultry culture and the treatment of their excreta to compost. Some wasteland or wastepool can also be used to culture *Azolla*, grass and green manure. City garbage and nightsoil can be made to compost and waterlogged sludge can be extracted from the bottom of pools or rivers. All these wastes contain a considerable amount of plant nutrients which can be returned from non-cropped to cropped areas.

TRANSPORTATION OF PLANT NUTRIENTS IN CHINA

Each year 30 million tons of NPK pure nutrients are applied as chemical fertilizer to 100 million ha agricultural land. At the same time, there is also an input of the same amount of nutrients in the form of manure. The total amount of nutrients is thus 60 million tons, that is on average 51 kg plant nutrients per person, or 250 kg in terms of fertilizers, which are converted into 387 kg cereals, 4.9 kg cotton, 14.3 kg oil material, 73.7 kg sugar material and 27.5 kg meat *per caput*. The actual uptake of all this food and fibre is only about 100 kg of commercial fertilizer. In fact, the plant nutrients absorbed and used are only about 30-40% of the material being applied. As a result of this low efficiency a considerable part of these nutrients will be lost and pollute the environment. The most serious pollution is caused by urban wastes. A survey of 479 city or urban waste and nightsoil statistics indicates that in 1979 a total of 77.64 million tons of garbage and 78.00 million tons of nightsoil had been produced. Until 1991 only 27.64 million tons of nightsoil had been cleared by the environment sanitation organization. The total quantity of wastes amounts to 140 million tons, including the sewage and sludge, of which 50-60% will not be returned to the cropped areas. They are disposed of in suburban landfills and into the river, lake or sea.

In the countryside the farmers treat organic waste to make manure depending on the price of chemical fertilizer and on the cost of the farmers' labour. The social factor is more important than the ecology factor. Between 1988 and 1992 the price of chemical fertilizers has doubled, so that the farmer perceives organic manure to be cheaper than chemical fertilizer. Furthermore, government has adopted a policy to encourage farmers to use organic manure. In this way plant nutrient transfer from cropping area to the non-cropping area and the hazard of pollution will be changed. The proportion in which wastes will be returned to cropping areas will differ according to the Chinese economic zone distribution. Three zones can be distinguished: the Eastern coastal zone – an economically developed zone; the Middle China zone and West China zone. The two latter zones are considered developing areas in which the transfer of plant nutrients and the agricultural production differ from the more developed coastal region of East China.

TABLE 1
Plant nutrient situation and agricultural production in 1991

Zone	Area (million ha)	Cereal production (million ton)	Organic manure (million ton)			Chemical fertilizer (million ton)		
			N	P_2O_5	K_2O	N	$P_2$05	K_2O
East	33	160	3.57	2.30	4.73	7.12	1.81	0.72
Middle	47	180	4.11	2.49	5.57	6.50	2.18	1.51
West	30	100	4.93	2.69	5.93	3.50	1.01	0.14

East China includes 11 provinces, Middle China 9 and West China 10.

TABLE 2
Relationship between nutrient input and population

Location	Population million	Organic manure		Chemical fertilizer		Ratio organic/ chemical
		Total million ton	%	Total million ton	%	
East	426	10.6	35.3	9.7	39.0	1 : 0.94
Middle	472	12.2	36.4	10.2	42.0	1 : 0.84
West	280	13.2	39.3	4.6	19.0	1 : 0.35

TABLE 3
NPK ratio in organic and chemical fertilizers

Location	Org. manure			Chem. fert.			Total		
	N	P_2O_5	K_2O	N	P_2O_5	K_2O	N	P_2O_5	K_2O
East	1	0.64	1.32	1	0.25	0.10	1	0.41	0.54
Middle	1	0.60	1.36	1	0.33	1.36	1	0.46	0.70
West	1	0.55	1.20	1	0.29	0.04	1	0.44	0.72
Total country	1	0.59	1.29	1	0.29	0.14	1	0.42	0.63

Tables 1 and 2 show that the distribution of plant nutrients varies in the different areas. In Eastern China the population is considerably higher than in the other two zones. In this area agriculture is not a main source of income for farmers. Its organic manure input is lower and the chemical fertilizer input higher. In Middle and West China organic manure input is higher than in East China while chemical input is lower because of its cost.

These data reflect the relevance of the organic/chemical ratio to the farmers' economic condition and its direct influence on the efficiency of plant nutrients for crop yield. It appears that the role of organic manure is quite important everywhere in China since the $N:P_2O_5:K_2O$ balance depends on the organic manure input as shown in Table 3.

Table 3 reveals that it is in the West that chemical K_2O is very limited. However, the yields remain high and a great deal of the agricultural production is transported to Eastern

TABLE 4
Fertilization quantity of farmer input (kg/ha)

	Year	Manure	Cake	Chemical fertilizer				Total
				N	P_2O_5	K_2O	Complex	
East	1989	15900	60	219	60	6	24	309
	1990	15960	45	183	48	6	30	268
	1991	9330	45	201	54	9	36	300
Middle	1989	16830	30	138	57	6	10	213
	1990	12405	60	156	66	6	15	246
	1991	14460	60	162	72	6	21	264
West	1989	16260	15	108	42	3	15	171
	1990	20760	15	117	45	6	24	195
	1991	19930	15	120	48	9	27	204
Average	1989	16320	30	159	54	6	18	234
	1990	16305	45	156	54	6	24	237
	1991	15930	45	162	57	9	27	258

China. As a result plant nutrients from Western China are also transferred to the East so that plant nutrients must be supplied in the West through chemical fertilizers and transfer of nutrients from non-cropped areas. Because the arable land is only 10% of the total area in the West there is about 90% non-cropped areas which can be used to collect biomass and to make compost for application in the cropped areas. In Middle China rice is the first agricultural crop. Soils are deficient in K_2O, so that chemical potassium fertilizer is a main input in this area.

Table 4 shows that the organic manure application has decreased in the Eastern zone and that chemical fertilizer application there is higher than in the West by 50-60%. In West China economic development has been slower than in the East so that farmers have enough cheap labour to collect, transport and utilize organic manure. The economic condition of the farmer and unbalanced regional development are the most important factors of nutrient transfer. The average farmer's cash input in the Eastern zone is 692 yuang, in the Middle zone it is 315 yuang and in the West zone only 227 yuang. The East zone farmer's cash input is double or three times that of the farmer in the Western zone.

The application of integrated plant nutrition systems between 2000 and 2010 will result in major changes and new problems in China:

- The area of arable land will decrease at a rate of 1% each year while the population will also increase by about 1% each year. Farmers will move into the city or town or to the Eastern part of China mainly because of the great disparity of income between industry and agriculture which will lead to the contraction of agriculture.
- A marked increase in the use of chemical fertilizers will be difficult to implement because the cost of production of chemical fertilizer will rise too much. The use of high priced fertilizer may increase agricultural output but decrease farmer's income. In this way farmers will revert to organic compost utilization. While the production of bio-wastes and biomass will increase at the speed of about 5% each year, the people of China will demand improvement of environmental and ecologic conditions and of food

quality. Hence organic manure will still be an important source of plant nutrients toward 2000 and 2010 especially with regard to potassium.

- The need to apply fertilizer scientifically will be particularly felt in the Middle and Western parts of China. Because of the increased cost of labour the multiple crop index of arable land will not increase any further. It could be maintained at about 1.3-1.5. Fertilizer application will expand on cash crops, meadows, forests, fruits and Chinese medicines.
- By 2000 the yield of food will need to reach 500 million tons each year. At present, the requirement of plant nutrients is nearly 35 million tons of chemical fertilizers and 35 million tons of manure. By the year 2000 these requirements will increase by 5-10%. At the same time, nutrients will run off into surface waters and bio-wastes will become a major pollutant.

In the next years IPNS will require three fields of research in China: increase the yield of crops, increase farmers' income, and protect the environment.

WASTELAND UTILIZATION AND SOIL EROSION

In China soil erosion is a serious problem. For example in Sichuan province, the largest agricultural province of China, hills and mountains occupy 83% of the total area. Precipitation is more than 1000 mm/year, with the rainfall concentrated in summer. Soil and water losses affect about 250 thousand km^2, that is nearly 43.5% of the total area. Each year soil losses amount to 1 thousand million tons, which has already seriously affected soil fertility and plant nutrient transfer.

TABLE 5
Soil erosion and soil productivity

Erosion degree	Crop yield kg/ha				Average kg/ha/yr
	Rice	Maize	Wheat	Sweet potato	
Very strong	4860	2175	1500	2955	5715
Strong	6285	6945	3165	4410	8865
Nutrients lost %	22.7	68.7	52.6	32.1	35.5

Table 5 shows the nutrients that are lost and that are transferred from cropped areas into the river. In this province the sources of drinking water are wells, the depth of which is only 2-5 m, that is near to the surface of the paddy soil. In fact farmers are drinking paddy-soil water. Only 3% of the farmers use clean water from 100 m deep wells; 6% of the farmers use non-treated river water. Hence water source protection in relation with plant nutrient transfer is imperative in order to offset potential dangers for farmers and all of the people.

Farmers conduct some good experiments themselves such as the utilization of cultivated grass and green manure. Two kinds are very important: *Astragalus adsurgens* CV (the Chinese call it "shadawang") and *Sesbania*. They grow in both very arid and humid areas. Up to now they have been planted in zones higher than 2500 m above sea level. Their yield will reach 10-20 tons/ha. Their rooting system also extends widely, so that soil erosion can be decreased by 10-25%. Also sunhemp and peavine varieties in Southern China are effective for the conservation of water and soil. All these grasses and green manure can be used as fodder and moved to the cropped areas. China has 4 million ha of wasteland where grass and green manure could be cultivated.

According to experimental results different green manures have the following N fixation efficiency: soybean 57-92 kg N/ha/year; cowpea 80-84 kg N/ha/year; clover 104-108 kg N/ha/year; alfalfa 128-160 kg N/ha/year.

TABLE 6

Yield of "shadawang" at different levels above sea level (kg/ha)

Metres above sea level	One year	Two years	Three years
2250	3600	7237	18150
2520	3270	5550	8175
2662	3180	5325	8250
2950	-	1775	2550

NUTRIENT TRANSFER FROM FORESTS TO CROPPED AREAS

In some areas, especially on the vast plains of Middle China, farmers develop the agro-forestry system. Each 50 or 100 m of culture alternates with a zone of forest. The forested strips offer resistance to wind, absorb nutrients from deep below the surface and return them to the soil through leaf fall. Table 7 shows this benefit.

TABLE 7

Comparison between agro-forest and single crop (CK) systems of production (kg/ha)

Type	Tree (litter)	Wheat	Maize	Total	%
1	1947	11024	16588	29500	14.7
2	1773	10764	17920	30457	18.4
CK	0	11040	14670	25710	

These trees were grown for 6 years. Their density is 50/ha with an average height of 9-15 m, a width of the tree crowns of about 3-6 m and a radius of the tree trunk of 20-25 cm. In these conditions nutrient transfer and transportation from soil depth to the surface is very useful. Another way is to cultivate false indigo for example along railway roads, rivers, pools and on other wasteland. False indigo grows very rapidly. In only 1-2 years it becomes a good grove. The wood of it can be used for light industry, and its litter can be collected to make compost, the nutrient content of which is quite high. In recent years nearly 1 million ha of false indigo have been planted all over the country allowing for the transfer of 0.1-0.4 million kg NPK to cropped areas.

AGRICULTURE-ANIMAL SYSTEM

Animal excreta and their wastes are major sources of fertilizer for the transfer from non-cropped to cropped areas because most Chinese farmers feed animals with non-cultivated fodder, for example with grass, with green manure and with some light industry wastes. Animal excreta make up over 60% of total organic manure with a content of about 4-5 million tons N. This is a very large nutrient resource for cropped areas of which part will of course be lost.

Comparing the 1950s and 1980s, the application of chemical fertilizer increased 187 times while the use of organic manure increased only 8 times. The proportion of organic N to the total production N input dropped from 97% to 25% reflecting a sharp decrease of chemical fertilizer N efficiency.

TABLE 8

Animal protein N efficiency in different periods

Feed N input/animal N output							
1952	1957	1965	1970	1975	1980	1984	1988
18.5	16.4	12.2	13.2	11.6	11.0	10.5	8.3

From Table 8 it can easily be seen that, in the non-cropped areas, the efficiency of converting feed nutrient into edible animal production nearly doubled during the past 40 years. The N content of excreta, however, decreased per animal unit, but the total number of animals increased 3 times. Hence N nutrient transportation to cropped areas also increased 3 times. According to investigations one ha of grassland can produce 500 kg of animal produce and 2.5 tons of manure. If grass animal production were developed on 10 million ha, that is only 5-10% of the total area of grassland, the nutrient transfer to the cropped areas could reach 2 million ton NPK, that is about 1/10 of the total Chinese organic manure.

AGRICULTURE-FISHERY AND OTHER AQUATIC BIO-SYSTEMS

Cultured fish and other aquatic animals and plants are an important part of agricultural production. It is not only a support to food supply but it also absorbs more nutrients from non-cropped areas which can be moved into cropped areas to increase soil fertility. China has a very limited land area so that in recent years aquaculture research and extension have been greatly encouraged. Water hyacinth and *Azolla* are the best aquatic plants which grow in pools, ponds and sewage containers. Research was started in the paddy soil but has now expanded to non-cropped land on water-logged soils. According to experiments the average yield of aquatic plants can reach 100-160 tons/ha containing more than 1-1.3 tons/ha of NPK nutrients. In sewage treatment fields the cleaning process can yield NPK in the form of biomass.

TABLE 9

Sewage nutrient content before and after growth of aquatic plants (mg/L)

Treatment	NH_4-N	P	Total-N	NO_3-N
Before	16.9	7.6	28.0	1.2
After	6.1	2.7	12.0	0

The growing period is limited to about 2-4 months in the summer. The produce is taken out as a kind of feed for fish and pigs. The result is that 100 kg fresh fodder yield 1 kg of meat and produce 99 kg or organic manure.

In the *Azolla* experiment the nutrient distribution is shown in Table 10.

From this experiment it appears that over 77% of the biomass is converted to sludge which can be utilized by farmers as manure. The use of *Azolla* also yields more fish as food for people, as shown in Table 11.

These data indicate that aquatic plants not only serve as feed for animals but that a great part of their biomass can be transferred to cropped areas as an important supply of NPK nutrients.

TABLE 10

Nutrient distribution in fish fed with Azolla (%)

Muscle	6
Intestines	10
Stomach	2
Liver	2
Gill	3
Excreta	77

TABLE 11

Effect of Azolla feed on fish production (ton/ha)

	Azolla feed	Without Azolla
Grass carp	0.35	0.15
Carp	0.17	0.15
Luofe fish	0.54	0.40

TRANSFER BETWEEN COUNTRYSIDE AND TOWNS OR URBAN AREAS

With the adoption of reforms and a more open policy, urban construction has rapidly developed. The people's living standard has been remarkably enhanced and the urban environment has been noticeably improved. At the same time the disposal of nightsoil and garbage has become a big problem: how to collect, treat, transfer and return nutrients into the soil. According to statistics, nearly 300 million people live in the towns or cities. City administration systems manage to treat about 70-80% of the wastes. Each year as much as 28 million tons of nightsoil and 30 million tons of garbage are cleared away by the environmental sanitation organizations. These materials include a large part of plant nutrients that come from the cropped areas, but they can hardly be returned. Landfilling is the main treatment method. Some of the wastes are also disposed of in lakes and rivers.

Recently the government provides some financial support to the construction of factories making compost. As a result about 60% of city garbage can be used as compost and returned to the cropped soil, that is about 42 million tons of good quality compost with a nutrient content of 250 thousand tons N, 200 thousand tons P and 450 thousand tons K. Many experiments have fully proved that city garbage compost is a very good fertilizer for cropped land, especially for garden cultivation of cash crops, vegetables and flowers. Besides increasing the yield it can also improve the quality of agricultural produce. Table 13 shows the results.

TABLE 12

Urban resident and countryside farmer food consumption (kg/year)

	Cereal	Meat and fish	Vegetables
Average	450	40-50	300
Urban resident	300	70-80	320
Farmer	520	35-45	260

TABLE 13

Effect of using urban garbage compost on increased yield

Crop	Dose t/ha	Increase in yield %
Chinese cabbage	5-10	9-43
Cabbage	5-10	17-35
Wild cabbage	5-10	9-15
Lettuce	8-10	8-12
Pepper	5-12	10-11
Spinach	5-10	24-28
Tomato	5-10	8-10
Wheat	5-10	5-9
Maize	5-10	4-12

The collection, treatment and use of this kind of non-cropped area plant nutrients must be supported by the regional administrative offices, not just for economic reasons but also in order to solve environmental pollution by the city garbage.

NUTRIENT TRANSFER AND CHEMICAL FERTILIZER

To raise the efficiency of chemical fertilizer is not easy when large quantities are being applied. In recent years chemical fertilizer production, import and application have developed very quickly in China. However, the efficiency of chemical fertilizer has obviously decreased. Tables 14 and 15 show the research results.

TABLE 14

NPK efficiency in terms of yield levels of different crops (kg/kg)

NPK	Crops	No. of trials	<2250	2250-3750	3750-5250	>5250
			(kg/ha)			
N	Rice	896	8.6	10.9	8.6	6.9
	Wheat	1462	10.5	10.6	9.3	5.6
	Maize	728	16.2	13.8	13.5	10.7
	Sorghum	106	6.6	10.4	8.9	7.3
	Millet		39	5.6	6.2	2.8
P_2O_5	Rice Wheat	921	7.4	4.8	4.1	3.4
	Maize	1851	9.1	8.8	6.4	4.8
	Sorghum	1040	11.2	11.9	9.4	6.4
	Millet	129	8.4	7.8	5.1	6.2
		48	4.2	4.5	3.7	
K_2O	Rice	875	5.0	5.4	4.7	3.4
	Wheat	678	2.4	2.8	0.6	-1.0
	Maize	314	0.04	2.2	2.7	1.5
	Sorghum	11	-2.2	0	4.2	6.0
	Millet	45	0.9	0.7	1.4	

TABLE 15

Correlation of fertilizer use and grain production in China

Year	Chemical fertilizers million tons	Yield of grain	
		Total yield MT	kg/ha
1965	1.94	194.5	1635
1980	12.69	320.5	2745
1985	17.76	379.1	3484
1990	25.90	446.2	3930

Table 15 shows that from 1965 until 1990, a period of 25 years, the chemical fertilizer quantity increased 12.3 times, but that the grain production increased only 1.3-1.4 times. On the other hand the waste of agricultural energy increased nearly 20 times which entails an obstacle to current agricultural development. It has become more difficult than ever before to increase the yield of agricultural production as the cost/benefit ratio of agricultural inputs is increasing year by year. Concurrently the considerable flux of plant nutrients in the environment is becoming a marked source of pollution.

TABLE 16
Chemical fertilizer input ratio in the total cost (yuang/ha)

Crops	Wheat	Rice	Maize	Soybean	Cotton	Rape-seed	Ground-nut	Sugar	Fruit	Tea
Total input	1115	1500	900	435	1410	735	1350	3315	5505	2430
Chem. fert. input	517	537	471	97	675	465	315	1620	2715	795
Input ratio %	46.4	35.8	52.3	22.3	47.9	63.3	23.3	48.9	40.2	32.7

TABLE 17
Combined effect of organic manure and chemical fertilizer

Year	Organic manure t/ha		Chemical fertilizer kg/ha			Yield kg/ha
	Pig compost	Milk vetch	N	P_2O_5	K_2O	
1984	45	30	82	90	67	12450
1985	22	30	124	83	67	12300
1986	7	18	207	45	90	12600
1987	0	15	249	45	67	12900
1988	0	11	276	45	90	12750

Table 16 refers to five years of experiments on the combined use of organic manure with chemical fertilizer in rice, showing a yearly decrease of organic manure and an increase of the application of chemical fertilizer. The yield of five successive rice crops was maintained at 12 300-12 900 kg/ha. The efficiency of chemical fertilizer decreased progressively. In 1984-1985 the input of chemical fertilizer was 240-270 kg/ha yielding 12 450 kg/ha rice. In 1986-1988 the input of chemical fertilizer was 300-405 kg/ha yielding only 12 600-12 900 kg/ha rice. The increase of chemical fertilizer input amounted to nearly 50% but the yield of rice increased by only 1-3%. Hence, the influence of organic manure on the chemical fertilizer efficiency is very pronounced. A too high consumption of plant nutrients is partly wasted and adversely affects the water and air environment.

CONCLUSION

In China, the nutrients needed for plant growth are mainly supplied from chemical fertilizer and manure. However, until 2000 and 2010, the situation of combined chemical fertilizer with organic manure application techniques will change considerably on account of the higher costs of both fertilizer and labour.

The domestic production of chemical fertilizer (N, P_2O_5 and K_2O) will not suffice so that it will have to be supplemented by imports. The shortfall of P and K, especially K, can also be supplemented by applying organic manure. The results of countrywide experiments have shown that an application of 4.5 tons of plant residues or 15 tons of barnyard manure per hectare can provide enough potassium for the needs of crop growth.

The potential productivity of soil in China can be further increased by irrigating and by the application of fertilizer. At present, the grain yield can reach 15 tons per hectare in many parts of China, but the average yields are only 4-5 tons. It should be possible and easy to reach an average of 5-6 tons per hectare by 2000 and 2010.

Although the grain yield will continuously increase, the efficiency of fertilizer utilization will decrease. At present the use of 1 kg of fertilizer pure nutrient yields 8-10 kg grain. In 10-20 years, this ratio will come down to 6-7 kg and will probably drop to 4-5 kg in the Eastern part of China.

The efforts of improving farmers' benefits will evolve from monoculture to multi-agriculture systems. IPNS research should be extended to agriculture-animal systems, agriculture-forest systems, agriculture-fruit and village industry systems. All these subjects will need to consider four factors: (i) water source; (ii) farmers' income; (iii) environment and ecology' (iv) social factors. In China, as little as 0.1 ha arable land has to produce nearly 500 kg of food in order to meet people's living needs. This production level requires that due attention be given to crop variety, bio-techniques, soil fertility and plant nutrient supply. Considering the latter aspect it will be necessary to apply 80-100 kg NPK nutrients per person per year.

Each year a considerable amount of bio-wastes will be produced. They will need to be treated, transported, and finally returned to the cropped areas. This would be impossible if the government does not invest or provide financial support to solve this problem. On the other hand, since it is difficult to produce 500 kg of food on 0.1 ha arable land, further consideration will need to be given to the development of non-cropped areas including wasteland and water systems. In the developed Eastern part of China 20-30% of the total land is arable. In the Middle and West China about 50% and 90% of the total land area could be used for agricultural production. These areas could be developed to animal husbandry, pasture, forest and fruits, aquatic plant and animal products. Let these plant and animal nutrients be used by people, convert them into wastes and compost and transfer them to the cropped areas. This recycling system should be developed quickly so that, by 2000 or 2010, it could give the IPNS a new impetus.

Bio-fixation techniques will develop slowly year by year on account of the lack of consistency of the results that are obtained. Even so in the future the cultivation of legume crops will expand because their price will rise. Green manure areas and crop intensity indexes will decrease because the cost of farmers' labour will be too high to ensure economic feasibility.

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SESSION 4

Place and role of local and external sources of plant nutrients in cropping systems and their evaluation

Mineral fertilizers: plant nutrient content, formulation and efficiency

Crop yields in the majority of countries are low or very low and contrast unfavourably with yields in developed countries. Taking into account population growth and future land availability, major increases in crop yield will be needed by 2010 to achieve satisfactory average human nutrition. In some countries a radical alteration in agriculture will be needed. Many countries will need to raise yields by more than 50% and some by nearly 100%.

Soil fertility is crucial to obtain and sustain high crop yields. In many developing countries, serious depletion of nutrient status has already taken place, involving not only the macronutrients but, also, secondary and micronutrients. Much field research has shown high responses to the application of all of these, according to situations. Furthermore, crop nutrient removal data indicate the substantial levels of nutrients which must be made available for high yields. A comparison between typical fertilizer application rates in high yield (mostly developed) countries and low yield countries shows that with present practices, high yields in developing countries cannot be obtained. Much greater provision of a wide range of plant nutrients is essential.

Organic manuring can play a valuable role as organic materials generally supply all plant nutrients. However, their content may be low if the organic material was derived from a deficient soil. Furthermore, organic supplies are often limited, and this may be exacerbated as farm size diminishes, and organic manuring is often laborious and costly.

Most of the nutrients required for future high-yielding agriculture will have to come from mineral fertilizers, providing a range of nutrients, not merely one or two. This poses many problems in developing countries with regard to finance, cost, profitability, fertilizer availability, understanding by farmers and extension workers, availability of reliable information, etc.

CROP NUTRITION IN THE FIELD

In field agriculture, the plant dervies its nutrients from the soil in addition to whatever inorganic and organic nutrients sources may have been supplied by the farmer. In many situations, however, the soil itself is already depleted of nutrients and it is important to recognize the implications of this situation.

PAPER 4.1

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In the early years of use of a soil for agriculture, the first nutrient to be depleted is likely to be nitrogen. For most crop plants, a large supply of this nutrient is needed while nitrogen in the soil is normally transient, after breakdown of soil organic matter. Nitrogen must, therefore, be supplied from external sources (except to some extent for legumes). Where organic materials are insufficient, the external source means fertilizers. It is not surprising therefore that, in many developing countries, N fertilizers were the first to be used and are still predominant.

However, crop removal is by no means confined to nitrogen and the next nutrients to be depleted in relation to crop needs are phosphate, potash or both. While potash uptakes are much greater than those of phosphate, soil chemistry normally limits soil phosphate availability to a low level. As a result P_2O_5 and K_2O fertilizers have become widely needed, but to a varying degree depending on the soil type and crops grown.

Moreover, secondary (Mg, Ca, S) and micronutrients, although needed by crop plants in smaller quantities than N, P_2O_5 or K_2O, are also taken up and removed by every crop so that sooner or later the soil is unable to supply a sufficient amount of one or more of them for satisfactory crop production. In fact, many tropical soils are inherently supplied with some of these nutrients and have relatively low capacities for retaining them. Sulphur is now widely deficient in Africa, molybdenum in acid tropical soils, zinc in many rice and citrus areas, boron with regard to many soils and crops. The position in saline soils is particularly critical, because calcium carbonate renders many micronutrients, even if in good supply, insoluble. The micronutrient situation in the early 1980s was well researched by Sillanpää (FAO, 1982) and recently, micronutrients deficiencies and remedial treatments have been documented by Isherwood (IFA, 1991).

Since much higher crop yields will be required, in some countries in the immediate future, and in all countries in a foreseeable future, the question arises how these yield increases can be achieved in the face of low soil fertility and deficient crop nutrition. It is realized nowadays that efficient organic and other biological approaches can provide a greater level of plant nutrition than what could be achieved by traditional practices. A considerable advantage of organic manures is that, to a certain extent, they contain the whole range of plant nutrients, which most mineral fertilizers do not. However, with increasing intensification and in striving for much higher yields, it is doubtful that organic materials alone can provide an adequate level of nutrients save in exceptional circumstances.

Even with an active promotion of organic sources of plant nutrients toward achieving yields needed in developing countries, it appears unavoidable that the use of mineral fertilizer will need to increase considerably. Assuming that fertilizers are to be recommended, the next stage is for the farmer to have access to all of them, at the time they are needed and at an affordable price. This may be particularly problematic in a system where the supplier traditionally stocks only one or two fertilizers and sometimes only in limited quantities. Furthermore, fundamental problems of supply, transport, logistics and credit as well as policy matters at government level are also involved.

In developing countries many farmers have limited education and the complexities of applying three or more fertilizers in different quantities with different bag prices (and perhaps sizes) may lead to ineffective usage. 'Straight' fertilizers may be mixed on the farm; however, the proportions may be incorrect. Alternatively, the farmer must apply three or more separate materials, which is laborious. If a micronutrient for soil application is involved, there is the danger of overuse, which may lead to phytotoxicity.

IMPORTANCE OF FORMULATIONS AND FORMS OF MINERAL FERTILIZER MATERIALS

- **Straight versus multinutrient solid fertilizers**

A multinutrient fertilizer, as the name suggests, is one which contains two or more plant nutrients which have been deliberately included for nutritional purposes (i.e. not as carriers). They are often, but not always, composed of specific proportions of single or 'straight' fertilizers. In addition to the macronutrients, they may also contain secondary and micronutrients. They may be either solid or liquid. If solid, which is most common, they are also called 'compounds', although this is chemically incorrect. When compound fertilizers have been manufactured by a process involving strong or weak chemical bonding, they are called 'complex' fertilizers Compounds which are formed by simple physical mixing of the components are called blends. The use of these terms, however, is not always in line with these definitions.

The 'straight' or 'commodity' fertilizers, which are most frequently used in preparing compounds, are urea, ammonium nitrate (AN), ammonium sulphate (AS), single and triple superphosphate (SSP and TSP), muriate of potash (MOP, potassium chloride), sulphate of potash (SOP) and diammonium phosphate (DAP). The most common components of NPK compounds are AN, urea, DAP and MOP.

DAP is not normally considered a compound fertilizer, although it includes both N and P. However, it is frequently utilized in complexes and blends in combination with closely related monoammonium phosphate (MAP).

A solution to many of the problems prevailing in developing countries is the use of multinutrient, or compound, fertilizers. Whatever other advantages the latter have, overcoming these difficulties is undoubtedly of the highest importance. In sharp contrast to the situation in developed countries, nutritional problems in developing countries are likely to be more complicated or, at least, no less complicated, but since farmers generally have a lower standard of education, mistakes are more likely to be made.

A multinutrient fertilizer obviates problems caused by supply shortages that are common with individual fertilizers. If the distributors have any stocks at all, they will automatically be balanced and adequate. They will probably carry nitrogen for top dressing as well. Multinutrient fertilizers ease the difficulties of extension workers, both for themselves and for explaining to the farmers. In a carefully planned system of multinutrient fertilizers, the crops for which a product is recommended, the quantity required, even the time and method of application, storage and other information can all be printed (in words or pictures) on the bag. In China (UNIDO, 1991) a wide range of multinutrient fertilizers has been produced which goes as far as to provide specific compounds for various crops, e.g. for water-melons, on a range of soils.

A great advantage of multinutrient fertilizers in developing countries is that their composition can be determined by scientists and technologists who are most knowledgeable. Another advantage is that compounding mitigates a cost increase in one ingredient, which if bought separately, can depress purchases and lead to further unbalanced nutrition. Multinutrient fertilizers will undoubtedly play a vital role in establishing balanced crop nutrition in developing countries and this will be particularly true where organic manures are in short supply.

Multinutrient or compound fertilizers are combinations of straight fertilizers, or formed by chemical reaction of raw materials and may contain any number of nutrients. They are usually designated by their N, P_2O_5 and K_2O contents, e.g. 15-15-15, although some countries use different systems. Nutrients in compounds other than NPK are commonly designated, e.g. 6-18-15 + 9S + 0.1 B. Fillers may be used in solid compounds to adjust the nutrient composition for trade purposes; however, this increases direct and indirect costs per unit of nutrient.

Complex fertilizers are solid compounds which have been produced by processes involving strong or weak chemical bonding. They are normally granular.

Blends are produced by simple physical mixing of ingredients. Bulk blends are widely used in North America, Western Europe (where they are increasing their market share) and in several developing countries. Bulk blending plants are cheap and can be widely established. Extreme flexibility of product composition and of plant operation is an important feature. However, grain size distribution of all the ingredients must be homogeneous, or bulk blends tend to segregate. Special sized materials are available to avoid this problem, which has been severe, but sometimes at extra cost. It may be difficult to distribute micronutrient components evenly in blends but special techniques have been developed. Blending reduces critical humidity and blends should be used quickly and not be stored for long periods.

Bulk blends are not uniform in appearance and farmer acceptance may have to be won, especially by field demonstration of effectiveness. Compaction blends are physical mixtures which have been passed through a roller mill to form a sheet, which is then commuted to granule-sized particles. They avoid the segregation problem of bulk blends and look fairly uniform. They do not require special sized materials. However, the plants are more expensive than bulk blending facilities.

- **Composition of multinutrient solid fertilizers**

In a solid compound fertilizer, nitrogen may be in the ammonium, nitrate or urea form and the percentages are usually specified. Slow-release nitrogen is now sometimes incorporated. Phosphate is normally specified in terms of its water and citric acid solubility, which depends on the ingredients used. Potash is usually included as muriate (chloride) but sulphate (and rarely nitrate) is used for special purposes. Sulphur, magnesium and micronutrients are frequently incorporated in compounds, according to need. Micronutrient additions should be inexpensive. They should be encouraged provided their content in the compound is kept at a moderate level.

Experimental work in Europe, devoted to the comparison of complexes, bulk blends and straights, at equal nutrient application rates, has shown the granular complex to be superior to the blend. However, spinner-application of blends is unlikely in developing countries where manual labour is being used. The difference in crop effectiveness was found to be small and the difference in cost must be considered.

'Prescription fertilization' by blends is possible but its efficiency may be exaggerated, due to local soil variability. A limitation of the number of blends or complexes, which ensure reasonable suitability over a range of conditions, is more realistic.

There are cost differences in the production and distribution of various types of solid compounds. Generally bulk blends are appreciably the cheapest. The costs of compaction blends, steam granular complexes and chemical granular fertilizers increase in this order. However, issues specific to each country may favour one system over another. The argument that all compounds are more expensive than equivalent straights has little weight in developing countries. The correct economic evaluation should focus on output achieved for equal fertilizer expenditure. The key comparison may be between a balanced compound and unbalanced straights.

Imported fertilizers have high cost if quantities are small and this includes granular complexes. A limited range of imports does not cater for a wide suitability for crops and soils. Quality of compounds is essential especially when newly introduced, and is essential for their adoption by farmers. Legislation and monitoring are needed. Undesirable minor constituent features should not be expected in compound fertilizers.

Some developing countries already use a substantial proportion of their fertilizers as compounds but these tend to be countries with a small fertilizer sector, except for Thailand. More compound use generally ensures a better national nutrients balance. Potential for expansion of compound use is very great.

The form of nitrogen in a solid compound fertilizer can be water-soluble ammonium, nitrate or urea-based and frequently the percentages of each are specified; for example, 55% ammonium, 45% nitrate, or 'urea-nitrogen not more then 15%'. A recent development is to include a proportion of a slow-release nitrogen substance, like 'ureaform' (there are several combinations of urea with organic molecules available). At present such compounds are expensive and not widely used. However, their further development is much to be desired, in order to reduce the need for topdressing.

The phosphate component of compounds is usually derived from DAP, nitrophosphate, TSP or urea phosphates. The main consideration is their water and citric acid solubility. For different soils and crops these may be specified, thus 60% water soluble, 95% citric acid soluble, or 100% water soluble. Cost usually rises with increasing water solubility for nitrophosphate-based compounds.

Potash in compounds is always water soluble and usually in the chloride form (MOP). However, for specific purposes, such as chloride-sensitive crops like tobacco, certain soft fruits like strawberry, and sometimes in saline soils, the sulphate form (SOP) may be preferable. However, this option is not often implemented as K_2O from SOP usually costs more than twice that from MOP.

Sulphur in compounds usually comes from AS, SSP or SOP. Magnesium is usually included as sulphate (including kieserite, a double salt of potassium and magnesium sulphates). Micronutrients can be added as sulphates, chelates, sodium borate, sodium or ammonium molybdate, or combined with one of the principal components. It is important that they should be well dispersed through the compound and not interact with another ingredient to form an insoluble component, like ferric phosphate. A further consideration is that some micronutrient deficiencies may not be remedied best through the soil due to fixation by an oxide clay, or in a calcareous or sodic soil.

Micronutrient additions should be cheap and in small quantities. When adding too much, B may become phytotoxic and Zn may interfere with phosphate nutrition. As the same compound fertilizer may be used in successive seasons, it is better to rely on low contents, even if they are not fully adequate for the first crop.

- **Cost of multinutrient solid fertilizers**

The main question that usually arises in evaluating the agronomic effectiveness of solid compound fertilizers is how the different forms compare with one another and with straight fertilizers. A prime factor in comparing various types of solid compound fertilizers is cost. There are at least four elements to be considered. First is the capital cost of the plant. The second is the processing cost, including bagging, per ton of compound. The third element is the cost of raw materials, based on specifications needed. The fourth cost element is transport which is crucial for developing countries. Transport costs are based on each country's geographic and economic situation. A chemical granulation plant is unlikely to be feasible in a developing country until there is a rather high fertilizer use and preferably raw materials locally available, especially phosphate and ammonia. Such plants are normally found in developed countries and only in a few high consumption developing countries like China, India and Pakistan. Thus, for many countries, transport cost of granulated complexes will be freight, etc. cost from Europe or USA. Such costs would be much less from an indigenous plant in which local raw materials are used.

Transport costs for bulk blending and compaction blending are quite different. Most blending plants, having low investment cost, are usually located in the consuming country. The costs involved are the acquisition of the raw ingredients, locally or from overseas, plus the cost of inland bulk transport to the blending facility. Distribution cost of the blends would be small or near zero if sold at the factory gate.

It is sometimes argued that all compound fertilizers are more costly than equivalent amounts of straight fertilizers. This may or may not be true, but in cases where it is, another economic consideration has to be addressed. In developed countries, the farmers may well consider the advantages to themselves of either using a compound, whether complex or blend, or the equivalent amounts of straight fertilizers. In developing countries, this consideration may not carry much weight. Most likely, the farmers will not use equivalent amounts of straight fertilizers even if they are available. They may well spend their limited cash or credit resources on familiar fertilizers like urea or SSP, resulting in unbalanced crop nutrition. In fact the real economic comparison in developing countries is crop yield obtainable from a balanced complete compound fertilizer *versus* that from an unbalanced application of straights at the same cost in cash. While the cost per unit of nutrient may be lower in a straight fertilizer than in a compound, the crucial point is how much crop can be achieved for the same amount of money spent, i.e. the focus has to be on output value (and quantity) and not on unit input cost. Furthermore, this type of comparison may be more relevant than the concern as to whether a blend produces a slightly smaller yield response (if it does) than a granular complex.

There is no doubt that granular fertilizers are superficially more attractive than blends. Apart from cost comparisons and the question of possible greater effectiveness at equal nutrient content, their appearance is more attractive to the farmer. They store well and apply easily. However, in the early stages of fertilizer sector development, it may not be easy to obtain the most suitable granular complexes. If the latter have to be imported, costs may rise sharply with decreasing tonnage. For this reason, it may be much less costly in foreign exchange to buy a larger quantity of one granular complex than smaller quantities of two or more, even if the total quantity is the same. In this situation, suitability of the complex for some soil/crop combinations in the country is doubtful and local blends may be a better alternative. Finally, the high quality of compounds must be stressed.

On the whole, the compounding of nutrients into a complex fertilizer has no effect on the content of minor constituents, such as heavy metals and fluorine, in the original ingredients. Steam granulated complexes involve only weak chemical bonding and no extractive process. Bulk blends incur no chemical action whatsoever. The production of nitrophosphate in chemical granulation certainly releases hydrofluoric acid, which can attack the metal of the plant, but the remaining fluorine content is not expected to differ from other solubilized phosphate materials from the same mineral source. Angé (FAO, 1993) has prepared a comprehensive review of heavy metals and other hazardous products in soils, crops and fertilizers.

Twyford (1993) has reviewed the use of multinutrient fertilizers in developing countries. It was found that some countries were making relatively extensive use of compound fertilizers, while others, including some major fertilizer consumers, were not. The highest consumer of compound fertilizers in 1990-91 was India, with nearly 1.4 million tonnes of nutrients compounded. Only 6.6% of the nitrogen used in the country was in compound form but 19.1% of phosphate and 21.5% of potash.

In general it was found that the use of compounds increased proportionally with decreasing fertilizer use. Countries with small fertilizer sectors tend to use compounds to a greater extent. Countries using less than 20,000 t N in 1990-91 averaged 53% of N use in compound form, 83% of P_2O_5 and 73% of K_2O. It was also clear that countries using more compounds on the whole had a better nutrient balance than those which relied more or exclusively on straight fertilizers. Thus, low fertilizer users may have had inadequate nutrient application but to some extent a better balanced nutrient supply than the high fertilizer users. In the future, more and perhaps better suited compounds could be recommended for many countries.

Controlled-release fertilizer

The term 'controlled-release fertilizer' refers to fertilizers that for some reason release their nutrient content over an extended period. Potential advantages claimed for controlled-release fertilizers are increased efficiency of uptake by plants, minimization of losses by leaching, fixation and decomposition, and reduction of costs as a result of a lesser number of applications.

Numerous controlled-release phosphorus fertilizers are in use. Among them are ground-rock phosphate, partially acidulated rock-phosphates (PARP), basic slag, fused calcium-magnesium phosphate, etc. When soluble phosphates are applied in granular form, the reaction in the soil is delayed, and pockets of relatively soluble phosphates may persist at the granule sites for several weeks.

The need for a slow-release nitrogen fertilizer is much more acute than for phosphate or even potash fertilizer. In contrast to phosphate and potash fertilizers, there is seldom much carry-over of fertilizer nitrogen from one crop to the next, the residual effects being very low. One group of controlled-release nitrogen fertilizers comprises chemical compounds which are only slightly soluble in water or soil solution. Urea-aldehyde compounds are the principal representatives of this group. Urea-formaldehyde, usually called 'ureaform', is produced commercially. A wide range of materials and techniques has been explored for making controlled release fertilizers by coating soluble fertilizer materials with plastic films, resins, waxes, asphaltic materials or other barriers. Sulphur-coated urea and neem-coated urea are examples of these types of fertilizers. Some of the purposes of controlled-release (resistance to leaching, prevention of denitrification losses and delayed availability) may be attained by delaying nitrification of ammonium nitrogen. For this purpose numerous organic chemicals have been identified as nitrification inhibitors. They are helpful only when conditions favour high nitrogen loss from the soil, e.g. under heavy rainfall or heavy irrigation, or in coarse-textured soils. Controlled-release nitrogen fertilizers have proved useful for some field crops in some situations, e.g. when labour is scarce and expensive. Prospects for improvement of phosphate and potassium fertilizers through controlled-release seem less promising than for nitrogen.

LIQUID FERTILIZERS

The main liquid fertilizers are nitrogen solutions, foliar sprays and nutrient solutions used in fertigation.

Nitrogen solutions

Nitrogen solutions are chiefly concentrated solutions of urea and ammonium nitrate (UAN) for direct application to the soil. Solid materials providing phosphate and potash may be added. Dispersing agents are usually needed to maintain the suspensions. These materials are mainly intended for large-scale machine applications, and are therefore not well suited to small farm operations in most developing countries. However, in surface irrigation, nitrogen compounds, usually predissolved, may be added to the water in the technique known as 'water run'. Provided the irrigation water spreads evenly over the land and is not drained off, this technique can be a useful way of applying nitrogen. Usually, however, there are practical difficulties in obtaining very even water distribution and sufficient retention in the soil. Liquid nitrogen solutions are not used much in developing countries except in a few cases of 'water run'. Nitrogen solutions may also be added to centre pivot or mobile irrigation appliances. They are used in this way in Saudi Arabia, some North African countries and the French Antilles.

Foliar sprays

These are dilute nutrients solutions which are sprayed on the leaves of growing plants. Usually a surfactant is added to aid sticking and absorption. Foliar sprays can normally only supply small quantities of nutrients, even if repeated. They are commonly used as 'booster shots' of micronutrients (El Fouly, 1988), for which they are particularly suitable. In some cases, as in cotton and bananas, foliar sprays combine nutrient with pesticide or fungicide application. Materials used in foliar sprays are urea, sometimes MOP or SOP, and micronutrient formulations, especially chelates. Each crop must be tested for resistance to phytotoxicity and solution concentrations must be carefully adjusted to suit.

There is some evidence that sprays of macronutrients, applied at suitable stages of crop growth, can significantly reduce the requirement of solid fertilizers. If further validated this finding could be of considerable importance. Foliar spraying has the great advantage that any farmer can undertake it with simple, inexpensive equipment. Since one of the main constraints to increased fertilizer use in developing countries is cost, economy in requirements through more efficient plant uptake is an exciting prospect.

Probably the widest use of foliar sprays in developing countries at the present time is aerial application of urea solutions to bananas in central and northern South American countries. In large, centrally-managed plantations, such aerial sprays are given at specific times and also when, by leaf analysis, the nitrogen content drops below the prescribed level.

Fertigation

This technique is attractive and could make a considerable contribution in developing countries. Fertigation means the application of nutrients in irrigation water and its main development has been in conjunction with localized irrigation. The latter is of great importance itself as it is a very economical way of using irrigation water, which is often in short supply.

In drip irrigation fertigation, the nutrients are injected into the water supply and thus pass directly to the plant sites. Plant root systems tend to develop asymmetrically towards where the droplets fall and can thus efficiently intercept the nutrients, with least interference from the soil, such as phosphate fixation. As drip irrigation is continuous or intermittent through the plant's life, the nutrient content and balance can be adjusted to suit each physiological stage, making for very high efficiency of nutrition, with smaller applications. The pressure needed to drive the system is low so that energy costs are small. A typical installation might depend on a small pump raising the irrigation water to a height of 7-8 m above the field to be fertigated. Another advantage is that a field can entirelt and reliably be fertilized in a few minutes. Fertigation, properly practised, can result in very high crop yields.

From the point of view of fertilization, it is essential to maintain full water solubility in order not to clog the emitters and to ensure that the intended application fully reaches the plant. The materials used must, therefore, be completely water soluble or be filtered before injection into the system (like DAP). Further they must not react with one another to form a solid precipitate. Fertilizers which are commonly used are urea, AN, AS, MOP, SOP, potassium nitrate, MAP, DAP and magnesium sulphate (Ignazi, 1992). However, there may be a problem with phosphate precipitates, which is exacerbated if the water contains much calcium. In some systems, phosphate materials are applied separately from other fertilizers, and phosphoric acid is increasingly popular for this purpose.

Fertigation is sometimes said to be expensive because of the cost of the drip irrigation equipment. However, all irrigation is expensive and the cost must be judged against the crop yields achieved, which are usually much higher than for surface irrigation.

Fertigation is not suitable for all crops and soils. It is best adapted to crops which are grown as individual plants, like fruit trees, bushes, vegetables and cotton, but it is used in Hawaii on sugar cane. It is most suitable for light soils, although clay soils are also fertigated. Saline soils can be problematic unless irrigation is continuous and annual leaching/flushing is ensured.

There have been some applications of fertigation in developing countries especially in estate conditions, such as bananas and pineapples in the Antilles and coffee in Malawi. In Egypt, a major smallholder development is currently applying this technique on 700 000 acres (283 400 ha), with a target of 1.5 million acres (607 287 ha). It should be very suitable for this country with a very limited aea of available agricultural land *per caput*.

A further extension of the fertigation principle is hydroponics, or the use of nutrient film. These techniques avoid the soil altogether and produce extremely high yields but are very expensive to install and require highly skilled supervision and maintenance. Save for very special conditions, such as growing vegetables or high value horticultural crops in suburban areas where no suitable land is available, they may have little potential, in the near future, for developing countries.

Gaseous injection

This technique consists of the application of nitrogen to the soil (pre-planting) by injecting gaseous ammonia. Special equipment is used and the method is largely confined to North America where it is widely practised. In developing regions, gaseous injection seems limited to a few countries where the USA has extended this technique, e.g. in Mexico, Cuba and Argentina. However, Mexico is the only country today where ammonia injection contributes significantly to nitrogen fertilization.

Since gaseous ammonia contains 83% N, the volume of product needed to carry a nitrogen application level is much lower than for any other method. In this sense, gaseous injection is inexpensive. With suitable soil textures and moisture contents, gaseous injection can also be very efficient in terms of low losses.

CONCLUSIONS

Crop nutrition improvement will be a major strategy to improve yields and raise production. While organic resources should be used to the fullest extent, fertilizers will be needed in much greater quantities and over a much wider range of nutrients. The old practice of limiting fertilizer applications to urea, perhaps some DAP and little else, will not suffice. With farmer education often deficient, correcting and improving the nutrient status of soils for the benefit of the crops, which is frequently a complex issue, will require new approaches. Compound fertilizers, both solid and liquid, of various types and by novel application methods, will be a very important means of overcoming many difficulties. Skilled formulations of compounds can of themselves, or in combination with organic inputs, supply all the nutrients required for high crop yields. It is gratifying that some developing countries, mainly those with small fertilizer sectors, have already adopted compound fertilizers. However, a further expansion is greatly needed.

The development of an appropriate compound country policy will require that many issues be resolved: whether to encourage bulk blending or granular complexes or both; the extent to which fertigation should be introduced for specialized crops; how far foliar feeding can be applied to supplement nutrient uptake through plant roots; which place to give to controlled-release fertilizers.

In many countries, applied research and field demonstrations are needed to make comparisons between the agro-economic benefits from straights, blends or complexes, and to ascertain the best fertilizer combination value for a given limited amount of money available to the farmer. In such work, it is essential that evaluation take place in the local socio-economic context; data from developed countries are of little relevance, except possibly for technology.

In the quest for making optimum use of compounds, uptake efficiency will be of great importance. The very fact of using compounds will give the best opportunity to exploit all positive nutrient interactions, but combinations of techniques, such as using solid compounds and foliar spraying, may lead to a greater efficiency. This is important not only to avoid nutrient waste, which could lead to environmental hazards, but also to allow for the purchase of the greater quantities of fertilizers that will be needed in the future. This financial aspect will pose a major problem for farmers and whole countries. Utmost economy in fertilizer use will therefore be essential. Indeed, the only justification for a country spending a greater proportion of its resources on fertilizers will be if maximum amounts of agricultural produce result from it.

Nevertheless, much experience has already been gained in the use of compound fertilizers and research needs should not be allowed to delay their much wider adoption.

One very important policy decision in many countries will be the choice between the development of blends or a reliance on granular complexes. Cost and logistic factors will be crucial in considering this issue but it is important not to underestimate the advantages of blends. In this respect the experience of Europe, with its well-established fertilizer industry, must be carefully judged for its relevance to local conditions. The most important factor in deciding whether to promote blends is likely to be that of quality control. If this control can reasonably be assured, then blending would appear a promising prospect for many situations. If quality cannot be controlled, blending may be less attractive. However, the economic balance of a control system against the probable higher cost of granular complexes should be calculated. The quality of the latter, if locally made, also has to be monitored.

In developing a country policy for the use of compounds, feasibility and cost issues must be considered. Blending should not be 'downplayed' because of data and advice from Western Europe. Evaluations should be made in the local socio-economic setting.

International actions are needed to alert developing countries to future problems of agricultural production and to the role which improved crop nutrition and balanced fertilization should play toward food security.

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DEFINITION

Pruning N use efficiency by the crop (%Ncrop) can be defined as the crop N derived from the prunings per unit of added pruning N (equation 1):

$$\%\text{Ncrop} = \frac{\text{amount of crop N derived from pruning}}{\text{amount of added pruning N}} * 100 \qquad \textbf{(1)}$$

A high %Ncrop is the result of a high amount of pruning derived N readily available for plant uptake and a high plant demand for N. Both the aspect of pruning 'quality' (Swift, this publication) and synchronization of pruning N with plant demand are important.

In leucaena alley cropping systems, aboveground residues are added to the soil, 3 to 6 times yearly (Table 1). However, not all the applied pruning N can be taken up by the maize (*Zea mays*) and cowpea (*Vigna unguiculata*) grains (Tables 1 and 2). Moreover, additional N will enter the system through N_2 fixation by the cowpea crop.

TABLE 1

Amounts of N added in different prunings in Leucaena alley cropping systems in IITA, Ibadan, Nigeria

Hedge age (years)	Pruning activities (kg N/ha)						
	1st	2nd	3rd	4th	5th	6th	Total
2[1,2]	106	55	60	NP[7]	NP	NP	221
3[1,2]	172	142	66	NP	NP	NP	380
4[1,2]	161	80	79	NP	NP	NP	320
3[3,4]	129[6]			96[6]		NP	225
4[4,5]	112[6]			69[6]			181

[1] Means of fertilized (120-90-30 kg NPK/ha) and unfertilized plots.

[2] Van der Meersch *et al.* (1993).

[3] Means of fertilized (60, 120 or 180 kg N/ha) and unfertilized plots.

[4] Kang *et al.* (1981).

[5] Means of fertilized (70 or 140 kg N/ha) and unfertilized plots.

[6] 129 kg N/ha for the first 3 prunings; 96 kg N/ha for the 4th and 5th prunings; 112 kg N/ha for the first 3 prunings; 69 kg N/ha for the 4th to the 6th pruning.

[7] NP = no pruning activity.

The %Ncrop does not take into account whether the N that has not been taken up by the crop is available for a subsequent crop or lost from the system. Especially in alley cropping systems, the nutrients that are lost beyond the crop rooting zone may be recovered by the deeper-rooting hedgerow trees. Residue N can also be immobilized in the soil organic matter pool, or taken up by weeds, although the presence of the latter has been shown to be repressed by mulch additions. On the other hand, residue N

TABLE 2

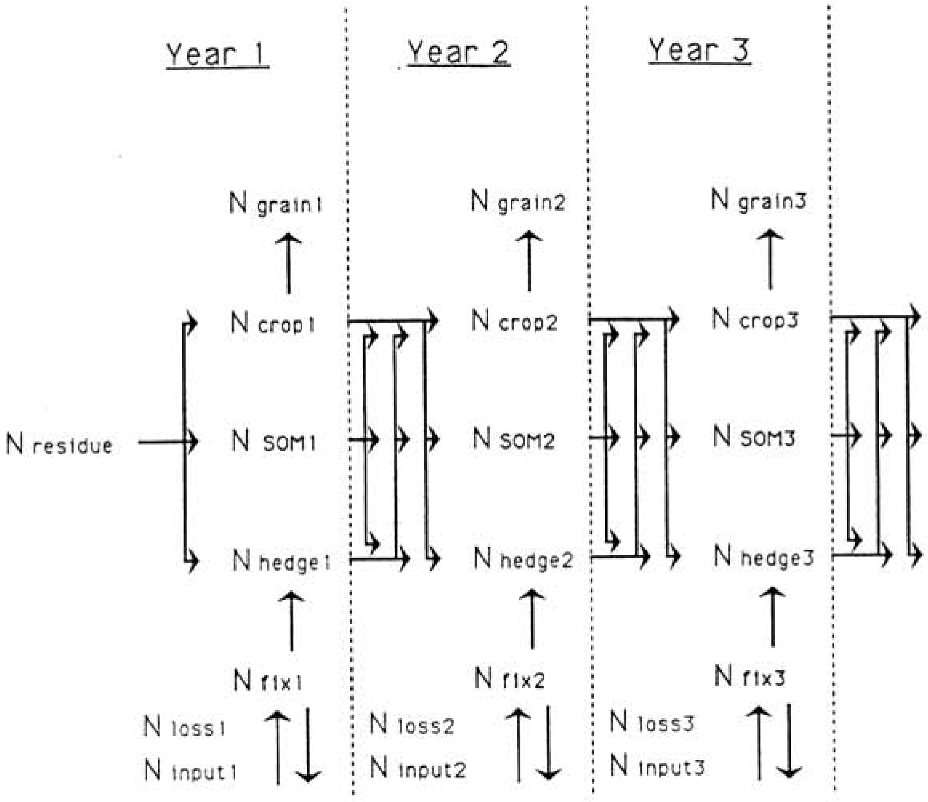
Total N content of maize (set at 1.5%) and cowpea (set at 2.5%) grains in IITA, Ibadan, Nigeria

Year	Maize N	Cowpea N	Sum
	kg N/ha		
1982[1]	38	13	51
1983[1]	37	13	50
1985[2]	70	16	86
1986[2]	50	20	70

[1] Kang *et al.* (1985).

[2] Siaw *et al.* (1991).

FIGURE 1
Components of the pruning N use efficiency by the system after n years of cropping (%Nsys$_n$). Nfix$_n$, Ninput$_n$ and Nloss$_n$ represent the input of N in the system through N_2 fixation or other mechanisms (fertilizer, deposition) and the loss of N from the system (leaching, denitrification, runoff or NH_3 volatilization). The other symbols are explained in the text.



can be lost through denitrification, volatilization, runoff, or leaching beyond the tree rooting zone. It is necessary to extend the pruning N use efficiency by the crop to the pruning N use efficiency by the system, which can be defined at year n after the pruning application (%Nsys$_n$) as in equation 2 (Figure 1):

$$\%Nsys_n = \frac{\sum_{i=1}^{n} Ngrain_i + Ncrop_n + NSOM_n + Nhedge_n}{N} residue * 100 \tag{2}$$

$Ncrop_n$, $NSOM_n$ and $Nhedge_n$ are the residue derived N, present in the above- and below-ground crop without the grains, soil organic matter and the above- and below-ground hedgerow. $Ngrain_i$ is the residue derived N present in the crop grains at year i. It is obvious that $Ncrop_n$ and $Nhedge_n$ consist of fresh organic matter when entering the soil system, while $NSOM_n$ consists partly of stabilized N, not mmuch being immediately available for crop growth.

TABLE 3

Different estimates of Leucaena N use efficiency by maize at the IITA main station in Ibadan, Nigeria

Methodology	Leucaena N (kg N/ha)			%Ndfp	%Ncrop
	1st	2nd	sum		
Conventional methods					
Alley cropping without pruning addition as control[1]	211	159	370	62.6	6.4
Continuous cropping as control[2]	-	-	187	33.0	17.6
^{15}N methods					
Direct (^{15}N labelled residues)[3]	78	-	78	10.1	10.0
Indirect (^{15}N labelled soil)[4]	198	164	362	19.8	6.3

[1] Mulongoy and Van der Meersch (1988).
[2] Van de Meersch *et al.* (1993).
[3] Vanlauwe *et al.* (1994a).
[4] Akinnifesi *et al.* (1994).

METHODOLOGY

Several methods have been used in the International Institute of Tropical Agriculture (IITA) main station, Ibadan, Nigeria, to measure the leucaena N use efficiency by maize with equation 1 (Table 3). The amount of crop N derived from the residue is calculated as the [percentage of crop N derived from the prunings (%Ndfp - equation 3)] * [amount of crop N].

$$\%Ndfp = \frac{amount\ \ of\ \ maize\ \ N\ \ derived\ \ from\ \ prunings}{amount\ \ of\ \ total\ \ maize\ \ N} * 100 \qquad (3)$$

Besides the climatological variation on a year-to-year basis, the amount of prunings, the method of pruning application and the method for estimating %Ndfp differed substantially.

The %Ndfp is higher with the conventional than with the ^{15}N isotope methods. In conventional methods, the pruning N use efficiency is measured as the N uptake in an alley cropping system with added residues, as compared to a control system without added residues. The choice of a suitable control is a major problem. If an alley cropping system without added residues is used as a control, the competition for other nutrients than N between the crop and the hedgerow might be reducing the crop N uptake. This will obviously lead to an overestimated %Ndfp. If a continuous cropping system without residue addition is used as a control, omission of the competition with the hedgerow may lead to an underestimated %Ndfp, while the lower availability of native N derived from the soil organic matter, due to a smaller input of organic residues, may lead to an overestimated %Ndfp.

In the direct isotope method, ^{15}N labelled residues are added, while in the indirect isotope method, the soil is labelled with a small amount of ^{15}N enriched fertilizer and unlabelled residues are added on half of the ^{15}N labelled microplot. The %Ndfp with the direct (%Ndfp$_{dir}$) and indirect method (%Ndfp$_{ind}$) is calculated with equations 4 and 5 respectively:

$$\%Ndfp_{dir} = \frac{maize\ \ atom\%\ \ ^{15}N\ \ excess}{residue\ \ atom\%\ \ ^{15}N\ \ excess} * 100 \qquad (4)$$

$$\%Ndfp_{ind} = \frac{maize\ \ atom\%\ \ ^{15}N\ \ exc.\ \ (with\ \ residue)}{maize\ \ atom\%\ \ ^{15}N\ \ exc.\ \ (without\ \ residue)} * 100 \qquad (5)$$

The isotope methods give a fairly similar %Ndfp, notwithstanding the much higher amount of applied N in two pruning activities in the indirect method approach as compared to the direct method approach (Table 3). The second pruning application has been shown to be better synchronized with the maize demand for N (Van der Meersch *et al.*, 1993), so a higher %Ndfp is expected in estimate 4. In the indirect ^{15}N method the underlying hypothesis is that the availability of the ^{15}N is similar with or without residue additions. Adding residues, however, increases the soil biological activity and may thus lead to a different soil N status as compared to the unamended microplot. It seems reasonable to state that, especially if the interest lies in drawing up a complete N balance, the direct labelling technique is the only way to get accurate figures of residue N uptake by maize.

In assessing $\%Nsys_n$, ^{15}N labelled residues are indispensable (Figure 1). So far, no measurements of the $\%Nsys_n$ have been reported, though some work is being done at IITA with ^{15}N labelled leucaena and dactyladenia (*Dactyladenia barteri*) residues.

SOIL ORGANIC MATTER QUALITY

Organic matter is converted to soil organic matter after addition to the soil. The distinction between organic matter and soil organic matter is not always clear. However, upon reaching the soil surface, fresh organic matter is potentially catabolized by the soil decomposer community and thus enters the soil decomposition subsystem as defined by Swift *et al.* (1979). *Organic matter* is considered as all organic residues, not in direct contact with the soil decomposition subsystem, *soil litter*, the organic components bigger than 0.25 mm in direct contact with the soil decomposition subsystem, and *soil organic matter*, the organic components smaller than 0.25 mm in direct contact with the soil decomposition subsystem.

The *quality* of fresh residues or *organic matter* has been assessed by measuring different biochemical properties which have been shown to delay or enhance the decomposition/N mineralization process (Table 4). High quality residues have been characterized by a low polyphenol content (Palm and Sanchez, 1990), a low polyphenol/N ratio (Palm and Sanchez, 1991, Oglesby and Fownes, 1992), a low lignin/N ratio (Melillo *et al.*, 1982, Kachaka *et al.*, 1993) or a low (lignin+polyphenol)/N ratio (Fox *et al.*, 1990). Polyphenolic components have been shown to react with residue N and render it unavailable for plant uptake (Palm and Sanchez, 1990), while lignin is a not easily decomposable cell wall polymer. A fast release of a high amount of N (or other nutrients) has been considered a prerequisite for a high quality residue. So far, the organic matter particle size (e.g. leaf size) has not been considered a quality parameter, but needs attention as a smaller particle size leads to a higher substrate - decomposer

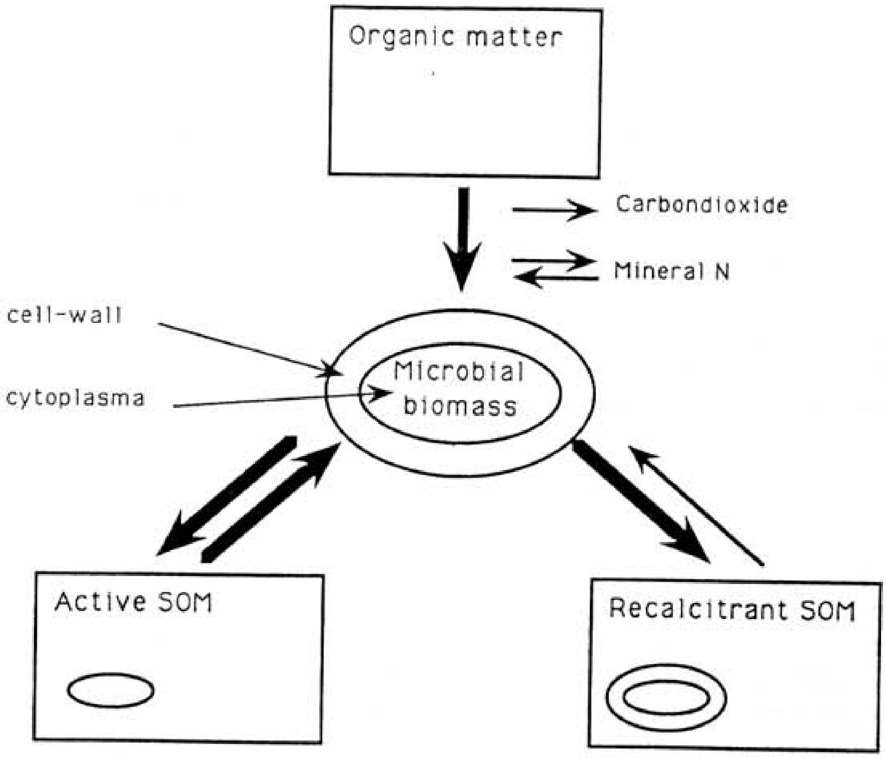
TABLE 4

Organic matter versus soil organic matter

	Composition	Quality parameters
Organic matter Soil litter	measurable (cellular)	nutrient availability
Soil organic matter	heterogeneous	nutrient availability physico-chemical properties

FIGURE 2

Microbial stabilization of fresh organic matter inputs. The arrow thickness corresponds with the rate of the process it represents.



community contact, resulting in a higher decomposition/N mineralization. The *soil litter* quality can be assessed in a similar way as the organic matter quality, as it consists of hardly decomposed material (Table 4).

If *soil organic matter quality* is to be defined, however, it is necessary to consider two additional features, which are less applicable to organic matter (Table 4).

First of all, the overall contribution of soil organic matter to soil fertility surpasses the nutrient release aspects. Besides releasing nutrients, soil organic matter also renders the soil physico-chemical environment more favourable for plant growth for most of the soils in sub-Saharan Africa. Swift and Woomer (1993) described how soil organic matter counteracts several constraints (low water availability, high soil erodibility, toxicity and low ion exchange properties) to crop production. Secondly, soil organic matter is a very heterogeneous substrate, composed of a whole range of substrates ranging from easily decomposable soluble organic components (active soil organic matter) over polysaccharides (intermediately decomposable) to highly undecomposable, humified macromolecules (passive soil organic matter).

In assessing the soil organic matter quality, it is necessary to (i) define biologically meaningful soil organic matter pools, (ii) determine the nutrient availability and contribution to the soil physico-chemical environment of each pool and (iii) determine the overall soil organic matter quality, taking into account the size of each pool. A testable hypothesis is that the larger, less decomposed soil organic matter pools (e.g. soil litter) will contribute more to the nutrient release processes, while the smaller, more decomposed pools (e.g. organo-mineral particles) will contribute more to a favourable soil physico-chemical environment due to their higher specific surface and/or surface charge. The criterion for the combination of different components in the same biologically meaningful organic matter pool should be based on their decomposability or availability for microbial breakdown, as this will determine their dynamics.

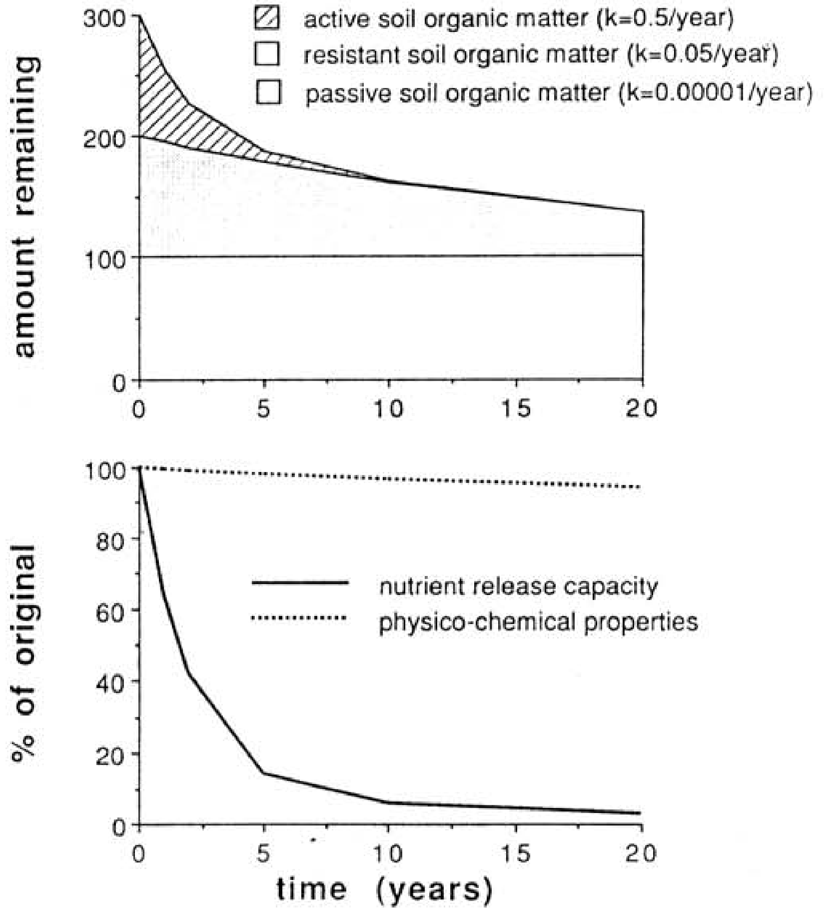
From the foregoing, it looks as if soil organic matter has to decompose in order to release nutrients, but at the same time should not decompose, in order to maintain the soil physico-chemical health. The breakdown of an easily decomposable substrate, however, leads to stabilization of part of the C through mediation of the soil microbial biomass, being the living part of the soil organic matter. One of the possible mechanisms is shown in Figure 2 where part of the decomposable C is converted into microbial cell-wall material, which is a considerably more recalcitrant substrate. Moreover, microbially formed polysaccharides can be physically protected from decomposition through the formation of stable soil aggregates (Stevenson and Elliott, 1989), while polymerization reactions occur between activated, microbially formed aromatic compounds and proteins (McGill *et al.*, 1981).

SOIL ORGANIC MATTER DYNAMICS

The total soil organic matter content of a soil in a steady state condition is constant, because the fresh organic matter input balances its decomposition. If a natural forest is cleared for cultivation, a drop in total soil organic matter content has been observed due to the imposed imbalance between fresh organic matter input and decomposition (Vlek and Koch, 1991). Moreover, the short-term decrease in microbial biomass C is much more pronounced than the decrease in total soil organic C (Ayanaba *et al.*, 1976). This indicates that if no fresh organic matter is added, the composition of the soil organic matter tends to shift towards the less decomposable or more recalcitrant end.

Soil organic matter quality is not a static parameter. Especially the nutrient release capacity of the soil organic matter will be affected in the absence of any fresh residue addition, as hypothetically shown in Figure 3. A method is needed to measure the active soil organic matter in order to understand its dynamics and its contribution to the soil N status. The microbial biomass, which can be relatively easily measured, is considered to be part of the active soil organic matter fraction. Adding fresh organic matter, however, has been shown to increase the microbial biomass content for a longer period of time (Kachaka *et al.*, 1993), indicating that active soil organic matter also includes non-living soil organic matter. A floatation method has been promoted by the Tropical Soil Biology and Fertility (TSBF) programme (Anderson and Ingram, 1993) to separate the soil litter fraction (Figure 4). Figure 5 compares the N release rate from the total soil litter as measured with the floatation method with the N release rate of surface litter as measured with the litterbag technique (Vanlauwe *et al.*, 1994b). A faster N release rate from the soil litter can be the result of a better contact

FIGURE 3
Hypothetical changes in soil organic matter quality in the absence of fresh organic matter inputs



between the residue and the soil decomposer community in the absence of confinement. This statement, of course, only holds if no excessive leaching of N occurs during the floatation procedure.

SOIL ORGANIC MATTER DYNAMICS AND RESIDUE N USE EFFICIENCY IN ALLEY CROPPING SYSTEMS

In a single growing season, there are several inputs of fresh organic matter in a leucaena alley cropping system. Besides the addition of above- as well as below-ground tree and crop residues at pruning and at harvest, there is a continuous input of active organic matter through root turnover and exudation. The quality of these residues varies drastically (Table 5). The amount of aboveground tree residue N added to the soil with the first and second prunings is indicated in Table 1. Smucker *et al.* (1994) estimated that during 14 weeks of

FIGURE 4
Sketch of the floatation apparatus used for separation of the soil litter fraction

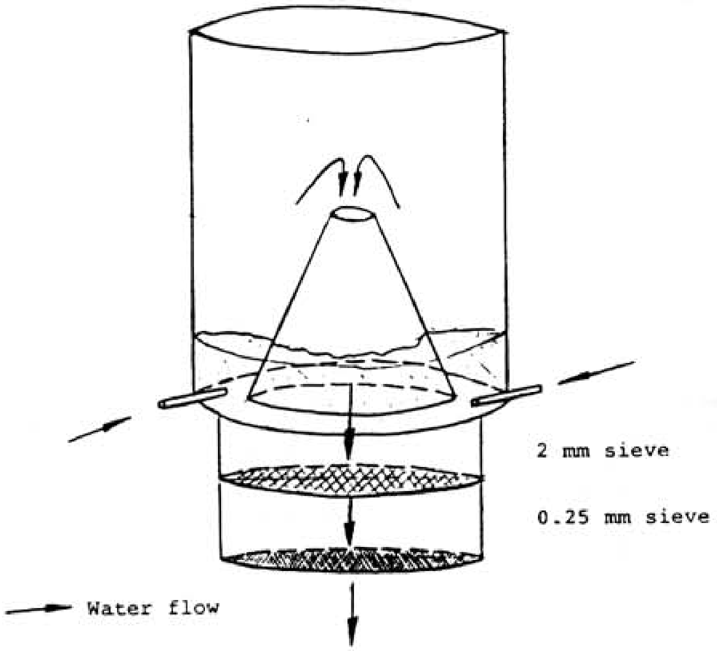


FIGURE 5
N release of leucaena residues measured with the floatation and the litterbag method. The N release rates were reported by Tian *et al.* (1992) (k = 0.0210/day) and Vanlauwe *et al.* (1994b) (k = 0.0147/day).

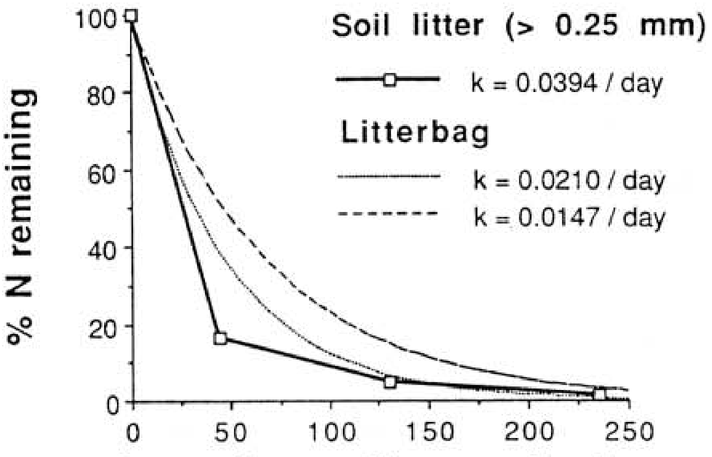
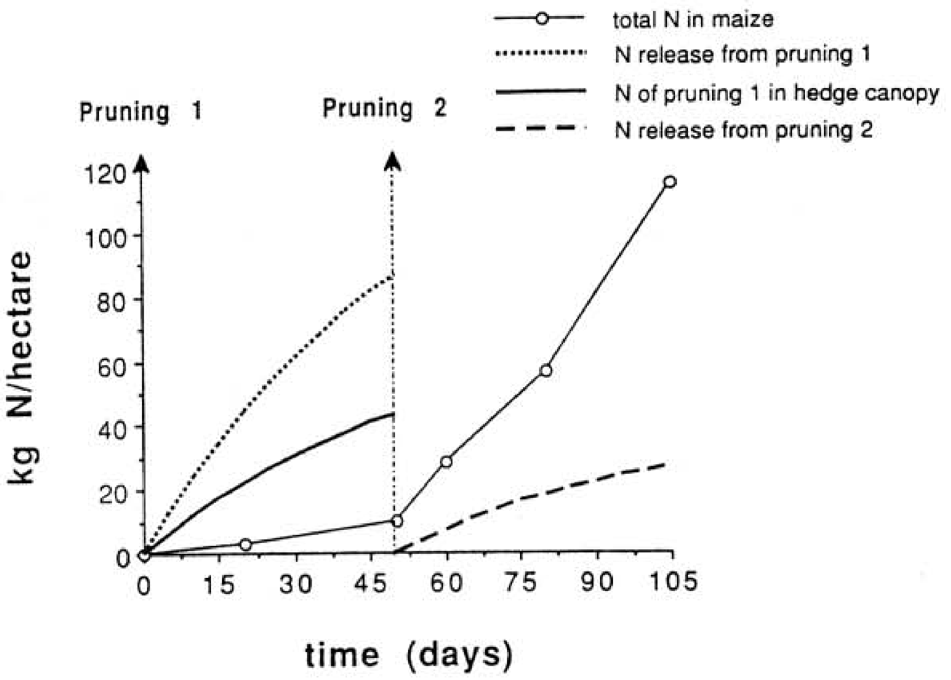


TABLE 5
Reported quality of the organic inputs in a leucaena/maize alley cropping system

Source	Quality			
	%N	C/N	% lignin	% polyphenol
Tree leaves[1]	4.33	9.8	8.1	3.37
roots[2]	2.09	16.9	24.8	1.94
Crop stover[3]	1.00	42.6	6.8	0.56
roots[2]	0.88	41.4	11.4	0.82

[1] Kachaka *et al.* (1993).
[2] Risasi *et al.* (unpublished results).
[3] Tian *et al.* (1992).

FIGURE 6
First pruning N taken up by the hedgerow canopy is better synchronized withe crop demand for N, when released from the second pruning. The maize N uptake curve was reported by Van der Meersch *et al.* (1993), the amount of N applied with the first pruning is assumed 146 kg N/ha (mean of the amounts, reported for the first pruning [Table 1]), the decomposition rate of both prunings was set at 0.0179/day (mean of reports mentioned in Figure 5) and 50% of the released N is assumed to be taken up by the hedgerow canopy.



maize growth, 91 and 102 kg N/ha may have been released by decomposing maize and leucaena roots, respectively. Whether pruning of the aboveground tree canopy stimulates the dying back of below ground tree roots has not yet been resolved. However, a study by Sanginga *et al.* (1990) showed that nodule senescence and decay occurred within 3 weeks after each cutting, new ones being formed to continue N_2 fixation during regrowth. This suggests that fine roots might have the same turnover.

Input of each of these fresh residues in the soil initiates their decomposition and N release, the rate of both processes depending on the residue quality. The N not taken up by the crop can be prevented from loss by incorporation in the deep-rooting hedgerow trees or by immobilization in the soil organic matter. In the first case, the N is returned to the soil in an easily available form with the following pruning, or through root turnover, which might be better synchronized with the crop demand for N (Figure 6). In the second case, the quality of the soil organic matter pool in which the N is incorporated will determine its availability for plant growth.

In Table 3, both isotope methods indicate a very low %Ndfp. In the case of the rapidly decomposing, N rich leucaena residues, however, a substantial amount of mineral N is available shortly after pruning application. The low %Ndfp must be caused by a lack of synchronization between the leucaena N release and the maize demand for N. This is especially relevant for the first pruning after the dry season, as this pruning contains the highest amount of N (Table 1), while at the time of its application the young crop is not able to withdraw a significant amount of the mineralized N. This observation again illustrates the necessity to extend the %Ncrop to the $\%Nsys_n$.

If observed %Ndfp's are very low, that means that the major part of the plant N is derived from other sources than the added prunings. This might be the residual soil litter, or the tree/crop roots. It is necessary to understand fully the origin of this non-residue derived N, as it seems to be better synchronized with plant demand.

MANAGEMENT OPTIONS AVAILABLE TO INCREASE THE PRUNING N USE EFFICIENCY BY THE SYSTEM

In order to develop management strategies, aiming at increasing the $\%Nsys_n$, it is necessary to understand fully the N pathways in the alley cropping system. ^{15}N isotopes will remain necessary to quantify the different processes unequivocally. Major difficulties are experienced when trying to measure the N losses in the form of denitrification, leaching, runoff or NH_3 volatilization. Quantification of these processes, however, is vital to derive proper management strategies, as the nature of the major N loss will determine the nature of the management practices.

The advantages of alley cropping are mainly related to the presence of hedgerow trees. Both the time of residue application and the amount of residue can be altered to improve the %Ncrop. Other hedgerow management options, however, remain unexplored. Although it is known that increasing the pruning frequency reduces the total amount of dry matter production (Duguma *et al.*, 1988), each pruning activity normally consists of a complete removal of the leucaena canopy. This, however, leads to a substantial amount of available N present in the soil solution through residue decomposition, and at the same time reduces, if not completely inhibits, the ability of the tree to absorb N, leached beyond the crop rooting zone, especially in a humid environment. Especially for the first pruning, when no crop is present or mature enough to absorb a lot of N, this might cause high N losses. Moreover, before the first pruning, a high amount of surface litter is already present, accumulated through dropping of leaves during the dry season. It might be necessary to think in terms of 'partial pruning' to increase the %Ncrop since pruning part of the canopy reduces the crop/tree competition for light, and leaves part of the canopy thus reducing the amount of added residue N and maintaining the ability of the trees to absorb N. Quantification of the root turnover, as influenced by the nature of the pruning activity, is urgently needed.

Synchronization of plant available N with crop demand can also be improved by manipulating the quality of the applied residues. Mixing the high quality leucaena residues with lower quality litter (higher C/N, less easily decomposable) might stimulate the immobilization of N in the soil organic matter pool, thus reducing its potential loss. Crop stover, returned to the soil after harvest, could be such a low quality material (Table 5), accompanying the first pruning of the second season.

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Integrated phosphorus management: a modified Mitscherlich equation for predicting the response to phosphorus in dryland agriculture

Phosphorus deficiency is a major constraint limiting crop production in rainfed agricultural systems in semi-arid zones, in particular in the lower-rainfall environments, where the prevailing low moisture contents limit the mobility of P in soil and the uptake of P by the crop (Penning de Vries and Djiteye, 1982; Ryan, 1983; Harmsen *et al*, 1983; Koala *et al.*, 1988; Matar *et al.*, 1992). Adequate P nutrition of the crop will increase yield, provided other nutrients and moisture are not limiting, increase root development and thus increase the effective soil volume from which the crop can extract water and nutrients, and advance physiological maturity. The latter phenomenon can be critical in escaping drought in environments that are characterized by increasing moisture stress towards the end of the season (Jackson, 1977; Cooper, 1983).

The major technology used to alleviate P deficiency in soils is the use of chemical P fertilizers. Often the recommended rates of application of P fertilizers are based on trials conducted under the aegis of FAO, as part of the FAO Fertilizer Programme, which started in 1961. In this worldwide programme, optimum levels of NPK were established for different crops in each of the participating countries (FAO, 1981; FAO/FIAC, 1987). The existing fertilizer recommendations, however, generally do not explicitly consider such factors as the extractable soil-P contents, the effect of organic sources of P, differences between soil types, residual effects of fertilizer-applied P and the build-up of available P in soils in time.

The objective of this paper is to discuss some elements of integrated P management, with emphasis on rainfed semi-arid cropping systems in the semi-arid climatic zones. A modified Mitscherlich equation is presented, which considers the effect of available moisture on potential yield and thus on crop demand for P, and which separates between the effects of initial extractable soil P, residual fertilizer-applied P and directly applied P fertilizer. Some data from experiments in Syria will be used to illustrate the use of the modified Mitscherlich equation.

PAPER 4.3

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INTEGRATED NUTRIENT MANAGEMENT

The objective of integrated nutrient management is to supply crops with sufficient nutrients for specified levels of production, within defined rotational systems, through a combination of soil, crop, water, organic matter and nutrient management, considering nutrients from all available sources, inorganic as well as organic. The broader objectives of integrated nutrient management are:

- to increase the availability of nutrients from all sources in the soil during the growing season;
- to match the demand of nutrients by the crop and the supply of nutrients from all sources through the labile soil nutrient pool, both in space (the rooting zone) and time (the growing season);
- to optimize the functioning of the soil biosphere with respect to specified functions, such as the decomposition of organic matter (mineralization), the control of pathogenic organisms by their natural enemies (predators), the biological formation of soil structure (aggregates, biopores), the decomposition of phytotoxic compounds, etc.; and
- to minimize the losses of nutrients to the environment, e.g., through volatilization (ammonia volatilization and denitrification in the case of nitrogen), surface runoff and leaching beyond the rooting zone (Harmsen, 1991; 1992).

It should be noted that integrated nutrient management is closely linked with soil and water conservation, and the integrated control of weeds, pests and diseases. The increased biomass production, due to better plant nutrition, increases water use efficiency by the crop, largely through increased transpiration and decreased soil evaporation, increased penetration of rainwater in the soil and decreased surface runoff. The more favourable soil water balance, the increased vegetational cover and the improved soil structure (stability, porosity), decrease losses of soil, organic matter and nutrients due to erosion and improve the physical and mechanical characteristics of the surface soil. The higher biomass production results in more crop residues and root mass being returned to the soil, thus increasing organic matter contents and biological activity in the soil. The enhanced activity of the soil biosphere may result in a better functioning of the soil ecosystem, e.g., through the control of pathogenic organisms, the decomposition of phytotoxic compounds in the soil, enhanced biological activity in the rhizosphere, etc. Hence, the nutritional status of the soil affects the ecological functioning of the soil-crop ecosystem and thus should be considered in designing strategies for soil and water conservation, and the integrated management of weeds, pests and diseases.

Integrated nutrient management differs from conventional nutrient management in that it more explicitly considers nutrients from different sources, notably organic materials, nutrients carried over from previous cropping seasons, the dynamics and transformations of nutrients in soil, interactions between nutrients, and the availability of nutrients in space (the rooting zone) and time (the growing season), in relation to the nutrient demand by the crop. In addition, it integrates the objectives of production, ecology and environment, that is, optimum crop nutrition, optimum functioning of the biosphere, and minimum nutrient losses or other adverse effects on the environment. Integrated nutrient management is an important part of any sustainable agricultural system (Harmsen and Kelley, 1993).

INTEGRATED PHOSPHORUS MANAGEMENT

The objectives of integrated P management are (1) to optimize the supply of P to each crop in a cropping system, at specified production levels and within a defined rotational context, and (2) to optimize the biological availability of P from all sources in soil. In order to improve the P nutrition of crops, the extractable-P contents in soil as well as the availability of P to the crop, in time and space, have to be increased through judicious management of the available resources: inorganic nutrient sources, organic matter, water, soil, and crop genetic resources.

To achieve these objectives, an integrated P management system would have to consider (a) all sources of P, (b) the chemical availability of P from different sources, and the transformation of labile into non-labile forms of P, as determined by soil, crop and environmental factors, (c) other factors that affect the availability of P to crops, such as temperature and moisture conditions, soil structure and the distribution and activity of roots, the role of VA mycorrhizae, the role of acidifying or complexing root exudates, etc., and (d) the crop requirements versus the availability of P, in particular the rates of uptake by the crop and supply of P in the soil, as functions of time (the growing season) and space (the rooting zone), as related to soil, crop and climatic factors.

Sources of phosphorus

Among the main sources of P are: native soil-P, both organic and inorganic; directly applied and residual fertilizer P; crop residues and roots; soil biomass; animal manures; and other organic sources, such as compost. Phosphorus in atmospheric deposition is considered to be negligible and P in irrigation water is not considered as the emphasis in this paper is on rainfed systems. Hence, integrated P management would focus on (a) fertilizer, both directly applied and residual, (b) crop residues, and (c) animal manures. In most cases it would be recommended to apply a mix of sources, inorganic and organic. The P from inorganic sources may be more rapidly available than P from organic sources, but the latter may provide a valuable source of 'slow-release' phosphorus. In addition, organic matter is the major source of energy for soil micro-organisms and adds to the soil organic matter content. Upon the decomposition of organic matter, organic compounds may be released that form soluble complexes with P and thus enhance the availability of P to crops.

Chemistry of phosphorus in soil

The inorganic (physical) chemistry of P in soils has been extensively studied but a number of issues remain to be clarified (Lindsay, 1979; Sample *et al.*, 1980; Barrow, 1983; Harmsen, 1984; Van der Zee and Van Riemsdijk, 1991; Matar *et al.*, 1992). Inorganic P occurs in several forms in soil, such as dissolved forms in soil solution, including orthophosphates, reversibly and irreversibly adsorbed forms associated with mineral and organic sorbent surfaces, and several mineral phases, ranging from surface precipitates (coatings) to discrete amorphous phases and crystalline forms. The chemistry of P differs between acid and alkaline soils: in acid soils Fe- and Al- phosphates predominate, whereas in alkaline soils Ca- and Mg-phosphates would be the thermodynamically stable phases. The irreversible adsorption of inorganic-P compounds in soils by Al- and/or Fe-oxide surfaces is referred to as 'P-fixation'. This process probably occurs in all soils that contain Fe- or Al-oxide surfaces, but is most pronounced in acid soils. The transformation of soluble P in alkaline (calcareous) soils to insoluble forms of P, such as apatite, is sometimes also referred to as 'P-fixation'. However, the mechanism of 'fixation' in alkaline soils (predominantly precipitation/mineral formation) is quite different from that in acid soils (surface adsorption followed by chemical bond formation). Also, the kinetics of the processes involved may be quite different, 'fixation' in calcareous soils may be much slower than 'fixation' in acid soils. Nevertheless, it is important to note that in virtually all soils, fertilizer applied P will be transformed from the initial, relatively soluble forms to progressively less soluble forms in the course of time.

Availability of phosphorus in soil

The availability of phosphorus to a crop is determined by the 'chemical' availability (i.e., solubility in an extractant solution) of P in the soil (Stewart *et al.*, 1988), and by a number of factors:

- spatial factors, such as the distribution of roots in the soil and the distribution of P, other nutrients, and water in the soil;
- physical and environmental factors, such as moisture and temperature conditions, soil structure and soil texture, transport properties, such as hydraulic conductivity and effective diffusion coefficients, and characteristic lengths and times in soil (Raats, 1990);
- physico-chemical factors, such as water holding capacity and adsorption capacity of the soil;
- chemical factors, such as composition of the soil solution and of the solid phase of the soil;
- crop-related factors, such as density and activity of roots, P-uptake characteristics, the composition of the rhizosphere; and
- other biological or physiological factors, such as the association of roots with VA-mycorrhizae, and the exudation of acidifying or complexing compounds by the roots.

For integrated P management an understanding of the (physical) chemistry of P in soil is essential, as the chemical availability of P in soil is affected by the rates of transformation of soluble or extractable forms ('labile' forms) to non-extractable or non-labile forms. The rates of transformation may depend on soil moisture and temperature conditions, the initial amount, distribution and chemical form of P in the soil or added to the soil, the chemical composition of the soil and the soil solution (in particular, pH), the presence of adsorbing surfaces, and the presence of organic matter and (organic) complexing agents that form soluble P-complexes.

The chemical availability of P applied to the soil may be influenced by the timing and type of P-application, the source of P used, crop residue management and the use of animal manures, and soil, water and crop management aimed at influencing soil moisture conditions and soil temperatures.

The availability of P to the crop further depends on the distribution of P in the soil, the activity and distribution of roots in the soil, and the conditions prevailing in the rhizosphere. Association of roots with vesicular-arbuscular mycorrhizae (VAM) may increase the P use efficiency, in particular under low P conditions. The association of VAM with roots may be influenced by inoculation with selected VAM fungi, by selection of plant genotypes that are conducive to colonization by efficient VAM fungi, and by establishing a soil environment favourable for the development of VAM fungi (Lee and Wani, 1991). Legume crops may excrete acidifying or complexing compounds through their roots, thus influencing conditions in the rhizosphere and increasing the utilization efficiency of P in cropping systems involving legume crops (Johansen and Sahrawat, 1991). Chickpea, for example, may excrete significant amounts of hydrogen ions and organic acids, and lower the rhizosphere pH by 1.0-1.5 units relative to the bulk soil, thus enhancing the solubility and uptake of P from the rhizosphere (Ae *et al.*, 1991a). Pigeon pea also lowers rhizosphere pH by excreting organic acids, in particular citric acid, but further increases the solubility of P in the rhizosphere by excreting several forms of tartaric acid. Tartaric acid is thought to chelate iron ions, thus releasing P associated with Fe-oxides and increasing the biological availability of P in soil (Ae *et al.*, 1991b). Hence, including crops that are known to solubilize soil P in crop rotations, selecting P-efficient varieties, or breeding for increased P-uptake efficiency, may help to increase the efficiency of utilization of P in cropping systems and should therefore be considered in integrated P management systems.

A MODIFIED FORM OF THE MITSCHERLICH EQUATION

The design and implementation of integrated nutrient management systems have to be supported by some form of conceptual, analytical or simulation models, to serve as a framework for the integration of the different components of such a management system. As an example of such an approach, a modified form of the Mitscherlich equation will be presented and discussed in the context of an integrated P management system for a wheat-lentil rotation in a Mediterranean-type environment.

Yield responses to fertilizer application and nutrient uptake by crops can be described by a classical Mitscherlich equation (Mitscherlich, 1913):

$$Y = Y_x - (Y_x - Y_0) * [\exp - (k * nf)] \tag{1}$$

where Y is the yield of a particular crop (kg dry matter/ha), Y_x is the maximum (potential) yield of that crop under the climatic and soil conditions of the experiment, Y_0 is the yield when no fertilizer is applied (nf=0), exp is the exponential function, k is a constant (kg/ha), which is a measure for the availability of the fertilizer nutrient to the crop, and nf is the rate of the fertilizer nutrient applied to the crop (kg nutrient/ha). The Mitscherlich equation assumes that only the nutrient under consideration is limiting crop yield, and that yields increase with increasing fertilizer rates until they asymptotically reach a maximum value.

Under rainfed conditions in semi-arid regions, potential yields of field crops are determined by available soil moisture (i.e., rainfall), if other factors are not limiting. This implies that for a particular crop, Y_x in Equation (1) is a function of rainfall, besides other factors such as crop genetic potential, radiant energy, temperature, etc. Assuming that Y_x is a function of rainfall, the Mitscherlich equation can be written as:

$$Y = Y_x(\theta) - (Y_x(\theta) - Y_0) * [\exp - (k * nf)] \tag{2}$$

where now $Y_x(\theta)$ is the maximum yield as determined by crop available moisture (kg dry matter/ha).

For a limited range of rainfall conditions, the relation between potential yield of a particular crop and seasonal rainfall (r) may be approximated by a linear relationship:

$$Y_x(\theta) = \alpha * (r - r_0) \tag{3}$$

where α is a coefficient (kg dry matter/ha/mm/y), which is a measure for the water-use efficiency of the crop, and r_0 is a constant (mm/y), which is a measure for the amount of rainfall that is lost from the soil through early or late rains. Further restrictions on the use of Equation (3) are that it would apply only to a limited agro-ecological range, where photoperiod, radiant energy, temperature, etc. would be similar, and to deep soils on flat land, where leaching losses and surface runoff would be limited.

The next step would be to consider all inorganic sources of P that are of relevance to the crop: viz. soil inorganic P, residual fertilizer P, that is, fertilizer P applied to a preceding crop during the previous season, and directly applied P fertilizer. Including these three sources of P in the Mitscherlich equation results in:

$$Y = Y_x(\theta) - Y_x(\theta) * [\exp - (k * ps + \varepsilon_r * pr + \varepsilon_f * pf)] \tag{4}$$

where ps is the initial P-Olsen content (mg P/kg)) of the soil (0-20 cm depth), pr is the rate of residual fertilizer (kg P/ha), pf is the rate of directly applied P fertilizer (kg P/ha), and k, ε_r and ε_f are constants. The dimensions of k, ε_r and ε_f are such that the expression to the right of the exponential function becomes dimensionless. Because all sources of P are included in the exponential function (Equation 4), Y_0 is set equal to zero, that is, when no P is available at all, the yield is assumed to be zero. Organic sources of P are not (explicitly) included, but ps may include some organic P, whereas the coefficients k, ε_r and ε_f may in part account for the effect of organics on the availability of these P sources in soil.

Finally, it is important to include the effect of available soil moisture on the availability of P in the soil. For example, in a study on the response of lentil to P fertilizer in southern Syria, it was observed that in medium- to high-rainfall seasons, near-maximum yields were obtained at lower levels of extractable soil P (P-Olsen) than in low-rainfall seasons (Matar, 1977). Similarly, at the same level of available soil phosphorus, P uptake by crops has been reported to increase with increasing seasonal rainfall (Marais and Wiersma, 1975; Olsen *et al.*, 1961). The effect of moisture can be accounted for as follows in the Mitscherlich equation (Harmsen, unpublished):

$$Y = Y_x(\theta) - Y_x(\theta) * [\exp - (k * ps + \varepsilon_r * pr + \varepsilon_f * pf) * \surd Y_x(\theta)] \tag{5}$$

where the factor $\surd Y_x(\theta)$ accounts for the effect of available moisture on the availability of P in soil. It should be noted that $Y_x(\theta)$ is a function of crop available moisture only, and thus is a measure for the availability of moisture in the soil.

The phosphorus use efficiency by a crop can be obtained by taking the partial derivatives in Equation (5). For native soil phosphorus (ps) the partial derivative becomes:

$$\partial Y/\partial ps = k * [Y_x(\theta) - Y] * \surd Y_x(\theta) \tag{6}$$

The use efficiencies of directly-applied (pf) and residual P (pr) can be obtained by taking the partial derivatives with respect to pf and pr:

$$\partial Y/\partial pf = \varepsilon_f * [Y_x(\theta) - Y] * \sqrt{}Y_x(\theta) \qquad (7)$$

$$\partial Y/\partial pr = \varepsilon_r * [Y_x(\theta) - Y] * \sqrt{}Y_x(\theta) \qquad (8)$$

It follows from Equations (6)-(8) that the P use efficiency is assumed to increase with increasing rainfall.

The use of the modified Mitscherlich equation (5), and all equations derived from that equation, assumes that the relation between potential yield and seasonal rainfall is known. This relation may be of the form of a linear relationship between yield and rainfall, such as in Equation (3), or may be derived from simulation models, or any other type of model. The relation can also be in the form of a tabulation of measured potential yields as a function of rainfall, that is, yields of crops grown under conditions free of constraints other than available moisture (and radiation, temperature, etc.), or obtained through interpolation from such data. It is essential, though, to note that the modified Mitscherlich equation can only be applied if the relationship between maximum yield and rainfall is known.

Equation (5) can also be used to assess yield as a function of ps at constant rainfall. For example, at zero P application (pf=pr=0), Equation (5) reduces to:

$$Y = Y_x(\theta) - Y_x(\theta) * [\exp - k * ps * \sqrt{}Y_x(\theta)] \qquad (9)$$

Hence, if $Y_x(\theta)$ is constant, Equation (9) is similar in form to the classical Mitscherlich equation (Equation 1), that is, Y is a function of ps only. Similarly, Equation (5) can be used to assess the values of ps required to achieve a particular yield (ps_c), expressed as a fraction of the potential yield, as a function of rainfall:

$$ps_c = [k * \sqrt{}Y_x(\theta)]^{-1} \ln [Y_x(\theta)/(Y_x(\theta) - Y)] \qquad (10)$$

where ln denotes the natural logarithm. Hence, assuming that potential yield is an increasing function of rainfall, it thus follows that ps_c is a decreasing function of rainfall. In other words, the value of ps required to achieve a particular yield target, say 80% of the potential yield, decreases with increasing rainfall.

PHOSPHORUS IN A WHEAT-LENTIL ROTATION IN SYRIA

Lentil (*Lens culinaris* Med.) is an important crop in rainfed farming systems in the Mediterranean environment of West Asia and North Africa. Lentil seeds are a valuable source of good quality protein in the human diet and lentil straw is a highly valued animal feed (Nygaard and Hawtin, 1981). Under rainfed conditions, lentil is generally grown in rotation after cereals, as is the case with other food and forage legumes in the Mediterranean region. The area under lentil crops is declining, however, because of the relatively high cost of lentil production (Khayrallah, 1981; Papazian, 1983). One way of reducing the cost of lentil production in a cereal-lentil rotation would be to apply P fertilizer to the cereal crop only. The success of this practice would depend on the ability of the lentil crop to benefit from the residual P of fertilizer applied to the preceding wheat crop.

In order to test whether P fertilizer application in a wheat-lentil rotation could be limited to the cereal phase only, a series of field experiments has been conducted at three locations in Northwest Syria during 1984-1989 by the International Center for Agricultural Research in the Dry Areas (ICARDA), Aleppo, Syria. The results of these experiments are reported in Matar *et al.* (in prep) and El Mahmoud *et al.* (in prep). The experiments aimed at studying the yield response of wheat to directly applied P and of lentil to directly applied and residual P fertilizer.

The experimental sites differed in long-term annual rainfall: Breda (281 mm/y), Tel Hadya (332 mm/y) and Jindiress (471 mm/y) (ICARDA, 1987). Prior to sowing, soils at all sites were sampled (0-20 cm depth) and analysed for $NaHCO_3$-extractable P (P-Olsen). All trials were conducted in three replications. The phosphorus fertilizer used was Triple Super Phosphate (44% P) and all plots received 60 kg of nitrogen per hectare (Ammonium Nitrate, 33% N), 20 kg at seeding and 40 kg topdressed in early February. During one growing season, durum wheat (variety Sham 1) was grown at the three sites, at different P application rates. During the following growing season, the durum wheat trials were repeated at the same sites, but in different fields. In the fields that had been under durum wheat during the previous season, lentil (variety Syrian Local Small) was sown at all sites. In the lentil-phase of the rotation, the main plots were split into subplots, where P was applied at different rates, banded with the lentil seed, such that the response of lentil to residual as well as to direct application of P could be compared.

Response of durum wheat to direct P application

The yield response of durum wheat to directly applied P fertilizer can be described by a modified Mitscherlich equation of the form (cf. Equation 5):

$$Y_w = Y_{wx}(\theta) - Y_{wx}(\theta) * [\exp - (k * ps + \varepsilon_f * pf) * \sqrt{Y_{wx}(\theta)}] \qquad (11)$$

where the subscript 'w' refers to wheat and pr has been set equal to zero. A linear regression of the values for the potential yield, estimated on the basis of Mitscherlich equations for the individual trials, on total seasonal rainfall for those trials, resulted in the following regression equation (cf. Equation 3):

$$Y_{wx}(\theta) = 30.68 * (r - 75.6) \qquad (12)$$

where $R^2=0.957$ (6 trials), that is, under the conditions of the experiments, rainfall was the single variable determining most of the variation in $Y_{wx}(\theta)$, as would be expected when nutrients are not limiting yield, and soil and climatic factors other than seasonal rainfall are similar among sites. Using Equation (12), the coefficients in Equation (11) were estimated to be $k=0.004847$ (0.000356) and $\varepsilon_f=0.000341$ (0.000060), where the standard errors are given in parenthesis and where the coefficient of variation for the pooled regression analysis was 0.940 (6 trials, 24 observations).

Response of lentil to directly-applied and residual P

For the analysis of the yield responses of lentils to directly-applied and residual P, Equation (5) can be written as:

$$Y_l = Y_{lx}(\theta) - Y_{lx}(\theta) * [\exp - (k * ps + \varepsilon_r * pr + \varepsilon_f * pf) * \surd Y_{lx}(\theta)] \qquad (13)$$

where the subscript 'l' refers to lentil. A linear regression of the potential lentil yields, estimated from the Mitscherlich equations for the individual trials, on seasonal rainfall resulted in:

$$Y_{lx}(\theta) = 20.56 * (r - 110.0) \qquad (14)$$

where $R^2=0.910$ (10 trials). Lentil yields increased approximately linearly with seasonal rainfall up to about 500 mm/y and then tended to level off with higher rainfall. Using Equation (14), the coefficients in Equation (13) were estimated to be $k=0.006091$ (0.000276), $\varepsilon_r=0.000333$ (0.000043) and $\varepsilon_f=0.000293$ (0.000049), where the standard errors are given in parenthesis and where the coefficient of variation for the pooled regression analysis was 0.984 (8 trials, 122 observations), that is, the regression was highly significant.

Response of wheat and lentil to P in a wheat-lentil rotation

At a seasonal rainfall of 300 mm/y, the use efficiencies of soil P by wheat and lentil become (cf. Equation 6):

$$\partial Y_w/\partial ps = 0.4022 * (6885 - Y_w) \quad \text{kg dry matter/ha/mg P kg}$$

$$\partial Y_l/\partial ps = 0.3807 * (3906 - Y_l) \quad \text{kg dry matter/ha/mg P kg}$$

which suggests that durum wheat would be more efficient in using native soil P than lentil (Figure 1). The P use efficiencies (Equation 6) for wheat and lentil can be written as:

$$\partial Y/\partial ps = k * (Y_x(\theta) - Y) * Y_x(\theta)^{-1} * Y_x(\theta)^{3/2} \qquad (15)$$

For $Y/Y_x(\theta)=0.8$ it follows that:

$$\partial Y/\partial ps = 0.2 * k * Y_x(\theta)^{3/2}$$

which is an increasing function of seasonal rainfall, assuming that Equation (3) holds. Figure 2 (left) shows that wheat is more efficient in using soil P than lentil, and that this tendency is more pronounced at higher rainfall. The soil P contents required to produce 80% of the potential yield can be estimated from Equation (10) as a function of seasonal rainfall (Figure 2, right). It follows that the soil P contents required to produce a certain yield, expressed as a fraction of the potential yield, decrease with increasing rainfall. In other words, under dryer conditions, higher P-Olsen contents are required to produce a given relative yield, even though potential yields decrease with decreasing rainfall.

The use efficiencies of directly applied fertilizer P by wheat and lentil follow from Equation (7). For example, at r=300 mm/y:

FIGURE 1
Use efficiencies of soil phosphorus by wheat (left) and lentil (right) as a function of actual yield at three levels of seasonal rainfall: 200, 300 and 400 mm y^{-1}

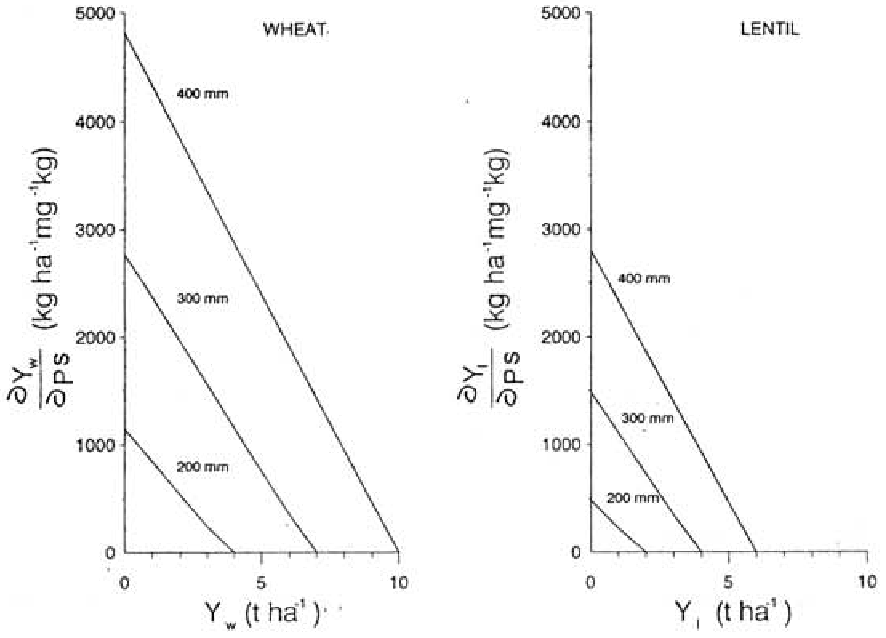
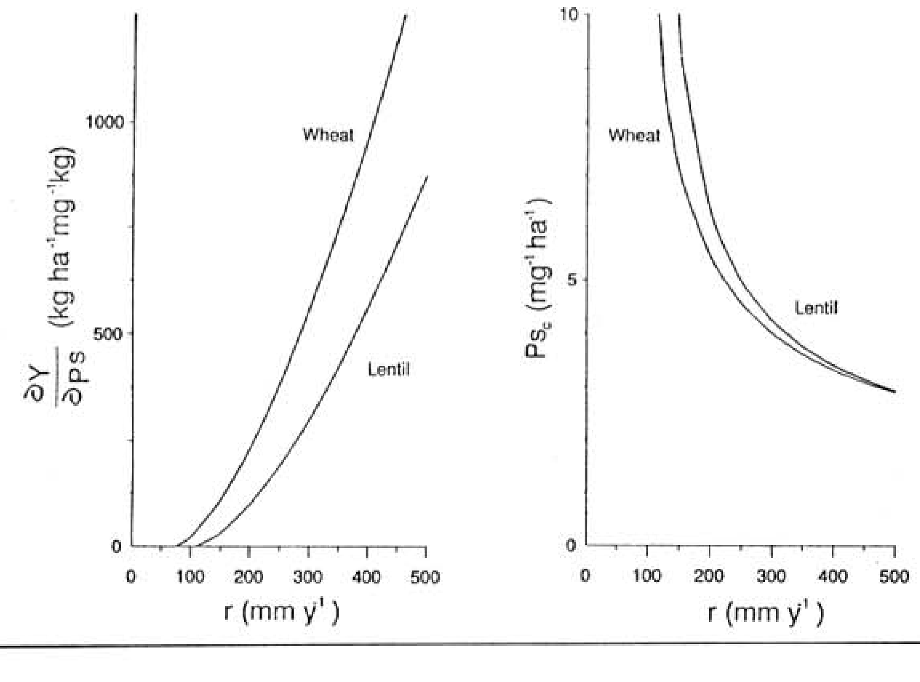


FIGURE 2
Use efficiencies of soil phosphorus by wheat and lentil as a function of seasonal rainfall, when the ratio of actual to potential yield is set at 0.8 (left), and the soil P contents required to produce 80% of the potential yield of wheat and lentil, plotted as a function of seasonal rainfall (right)



$$\partial Y_w / \partial pf = 0.0283 * (6885 - Y_w) \quad \text{kg dry matter/kg P}$$

$$\partial Y_l / \partial pf = 0.0183 * (3906 - Y_l) \quad \text{kg dry matter/kg P}$$

Examination of similar expressions for a wider range of seasonal rainfall suggests that in the range of 200-400 mm/y, wheat would be 2-4 times more efficient in using directly applied fertilizer P than lentil.

Finally, at 300 mm y^{-1}, the use efficiencies of directly applied and residual fertilizer P by lentil become at 300 mm (cf. Equations 7 and 8):

$$\partial Y_l / \partial pf = 0.0183 * (3906 - Y_l) \quad \text{kg dry matter/kg P}$$

$$\partial Y_l / \partial pr = 0.0208 * (3906 - Y_l) \quad \text{kg dry matter/kg P}$$

That is, lentil is about equally efficient in using directly applied and residual fertilizer P. This observation implies that lentil would benefit about equally from fertilizer P applied, in the previous season, to a preceding wheat crop, as from directly applied fertilizer P.

DISCUSSION

Under the conditions of the experiments referred to in this paper (Matar *et al.*, in prep; El Mahmoud *et al.*, in prep), the response of wheat and lentil at harvest to P was well described by a modified Mitscherlich equation. If Equation (3) holds, it follows that $\sqrt{Y_x(\theta)}$ is a measure for the 'effective' seasonal rainfall $(r - r_0)$ and thus is related to the available moisture in the soil during the growing season. As the availability of native and applied P in the soil is, among others, determined by the soil moisture content, it may thus be assumed that the factor $\sqrt{Y_x(\theta)}$ in Equation (5) accounts for the effect of soil moisture on the availability of P. The actual effect of soil moisture on the availability of P to a crop is slightly more complex, however, than would follow from the modified Mitscherlich equation in the form of Equation (5). This is because on the one hand the availability of soil P increases with increasing rainfall, but on the other hand the P requirement by the crop also increases with higher rainfall. The result of these two opposing effects is the factor $\sqrt{Y_x(\theta)}$ in the modified Mitscherlich equation for P (Harmsen, unpublished).

The conceptual advantages of the modified Mitscherlich equation, in the form of Equation (5), compared with the classical Mitscherlich equation (Equation 1), are that (a) one single equation is used to describe the yield response of rainfed crops to P fertilizer application, across sites and seasons, (b) the effect of rainfall on potential yield is explicitly considered, and estimated independently, (c) the effects of initial soil P (P-Olsen), residual and directly applied P fertilizer are estimated separately, and (d) the effect of $Y_x(\theta)$, that is, of seasonal rainfall, on the crop-availability of P in soil is explicitly considered.

The observation that lentil uses directly applied and residual phosphorus about equally efficiently, implies that lentil is relatively efficient in using residual phosphorus and relatively insensitive to a decrease in solubility of applied fertilizer P with time. Therefore, there would hardly be any use in applying P to the lentil crop in a wheat-lentil rotation and it would suffice to apply phosphorus to the wheat crop only, thus decreasing the production costs of lentil in a wheat-lentil rotation.

CONCLUSIONS

The response of rainfed wheat and lentil to fertilizer P in a Mediterranean environment could be described well with a modified Mitscherlich equation, which accounts for the effect of available moisture (rainfall) on potential yield and for the effect of soil moisture on the availability of native soil P, and residual and fertilizer P in the soil. The simple conceptual model underlying the modified Mitscherlich equation could contribute to the design of strategies for integrated P management in cereal-legume rotational systems. Further refinements of such a strategy would be necessary and could include the effect of organic matter on the availability of P in soil, the role of organic phosphates in the P nutrition of crops, and the selection of crop varieties that associate well with VA mycorrhizae and/or excrete acidifying or complexing compounds through their root system, which would increase the availability of P in soil.

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Contribution of nuclear techniques to the assessment of nutrient availability for crops

The basic concept underlying integrated plant nutrition systems is the maintenance and possible increase of soil fertility for sustaining enhanced crop productivity through optimal use of all sources of plant nutrients, inorganic and organic, including biological nitrogen fixation, in an integrated manner and as appropriate to each farming system under specific ecological, social and economic conditions. This concept has been advanced in part by means of experiments, conducted through the Coordinated Research Programmes, which were involved in a number of countries simultaneously. These programmes, therefore, gave results under a wide range of environmental conditions.

The Soil Fertility, Irrigation and Crop Production Section of the Joint FAO/IAEA Division, by using nuclear and related techniques, contributes to a better understanding of nutrients uptake by the plants in different soil and climatical conditions (IAEA, 1970a, b; 1974; 1978). As is known, only a fraction of the fertilizer applied to the soil is taken up by the crop. The rest either remains in the soil or is lost through leaching, physical wash-off, fixation by the soil, or release to the atmosphere through chemical and microbiological processes. Therefore it is necessary to obtain information on the relative merits of different fertilization practices such as methods of fertilizer placement, time of application and types of fertilizers. This information helps to achieve maximum efficiency of fertilizer use in the most economical way and reduce production costs to the farmers (Hera, 1979a; 1993; Hera *et al.*, 1984).

Since the plant does not discriminate between synthetic fertilizers or native soil nutrients, the exact amount of nutrients taken up by the plant from different sources can be measured only by using the isotope technique. The method used to solve these problems requires the introduction of known quantities of fertilizer labelled with isotopes into the soil at various times in different placements.

Isotopic-aided studies involve the application of isotopically labelled fertilizer as tracers, (with ^{32}P or ^{15}N for example), for quantitative and precise determination of the fate of specific nutrient elements in soil-plant systems. Frequently the isotope method is the only way to solve a particular question or to obtain specific information. Nuclear techniques provide direct and quick means to obtain the needed information resulting in high economic return and are normally complementary to conventional or classical techniques in agricultural

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PAPER 4.4
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experimentation. The general rule is to design simple experiments with concrete and well-defined objectives (Fried, 1978; Hera *et al.*, 1984).

It is essential for the fertilizer applications in the farmer's field to be made in such a way that crop will take up the nutrients from the fertilizer to the maximum extent, and therefore that the competing processes of fertilizer and soil nutrient uptake be reduced to a minimum. The combination of correct placement and time of application of field-applied fertilizer of appropriate chemical composition will tend to ensure the greatest uptake of nutrient from fertilizer by the crop with a minimum of fertilizer loss from interfering soil-fertilizer processes (Hera, 1979b).

Fertilizers labelled with the appropriate isotopes of interest will be invaluable tools for selecting fertilizer practices for different soils and climatic conditions, obtaining quantitative information on the efficiency of the use of nutrients from fertilizers by crops, studying nutrient movement in the soil-plant system and avoiding environmental pollution (Hera, 1993; Hera *et al.*, 1984).

The use of fertilizers and any other nutrient resources is frequently the most important factor for increasing crop production to a sufficient level. The more degraded the natural system has become, the less efficient is organic agriculture (FAO, 1992). The food requirements for the ever-increasing population of the world can be satisfied by applying improved technologies, adequate to different soil and climatic conditions. Nutrient mining could result in a soil fertility deterioration, which is no less dangerous than other forms of environmental degradation. Optimum fertilizer utilization, in an integrated manner, as appropriate as possible to each farming system, is imperative. Several efforts have to be made to manage and ensure the efficient use of nutrients for sustainable agriculture. The use of nuclear techniques represents an invaluable tool for maximizing nutrient utilization by the crops, in order to produce more and better food, to avoid pollution and to protect the environment, and provides the only direct means of following the fate of nutrients in soils and their uptake by the plants.

RESULTS AND DISCUSSIONS

A determination of the rate of a fertilizer to be applied is usually made by doing yield response experiments in the field (Fried, 1978; Hera, 1979a; 1993; Hera *et al.*, 1984). However, to obtain realistic data, the chemical and physical form of fertilizer, its interactions, time and method of placement, should be optimized before such field experiments are performed. The only way to measure what effects the chemical or physical form of the fertilizer, its placement or interactions with the main elements in the soil, the time of its application and cultural practices have on the uptake of fertilizer nutrient by different plants under field conditions, is to label fertilizer concerned with a suitable isotope of the nutrient and measure its uptake by the plant. Thus, a direct quantitative measurement of the effect of different management practices on fertilizer use efficiency can be made.

Some of the results of the research undertaken with fertilizers labelled with stable and radioactive isotopes in different countries through various Coordinated Research Programmes (Hera, 1979a, b; 1993; Hera *et al.*, 1984; IAEA, 1970a, b; 1974; 1978) facilitated by the Soil Fertility, Irrigation and Crop Production Section of the Joint FAO/IAEA Division are discussed below.

Assessment of nutrient availability from different forms and time of fertilizer application

The principle of assessing two different nutrients in one experimental plot can be utilized by labelling two nutrients in one compound such as both the nitrogen with ^{15}N and the phosphorus with ^{32}P or ^{33}P, in the ammonium phosphates, or by labelling two different sources of the same nutrient in the same chemical compound. The most important use of this latter principle is in the determination of the effectiveness for supplying nitrogen of the ammonium ion in NH_4N0_3 as compared to the nitrate ion. This was a particularly pertinent question that was dealt with by many international coordinated programmes (rice, wheat, maize fertilization). For rice fertilization programmes, one of the relevant questions was the possible use of NH_4N0_3 when this source of nitrogen was available to the farmer. The first results received from greenhouse experiments with the soils from the locations involved in the programme as well as from field experiments with NH_4N0_3 labelled with ^{15}N in both NH_4^+ and $N0_3^-$, $(^{15}NH_4)_2S0_4$ and Na $^{15}N0_3$ were convincing in showing that the nitrate portion of the ammonium nitrate is practically useless for paddy rice. Even when there was a cost advantage of NH_4N0_3, it would be more than offset by the low nitrate portion of NH_4N0_3 utilized by rice. (Fried, 1978).

Fried *et al.* (in Hera *et al.*, 1984) have pointed out that the ability to compare two sources of a nutrient in the same chemical compound is a special example of doing a field experiment without the problem of interactions due to the effect of plant growth, nutrient uptake or other factors that may be a result of the fertilizer treatment. This principle can be generalized for fertilizer forms and time of application by the appropriate experimental design. An example of such an experiment was given by the 1972-1973 Coordinated Research Programme of nitrogen fertilization for rice, using $(^{15}NH_4)_2S0_4$. The results presented in Table 1 show the different times of treatments which were utilized: the first, at transplanting 5 cm depth and the second, third and fourth at various times after transplanting. Basal treatment (T1) was usually found superior to an application three weeks later (T2). These results clearly show the most effective time for supplying supplementary nitrogen to a normal growing rice plant in so far as soil placement and nitrogen nutrition is concerned (IAEA, 1970b). While nitrogen supplied at least two weeks before the primordial initiation will almost wholly go into affecting the yield component if nitrogen supply is limited, applications at the time of the primordial initiation or later may not fully affect the yield component and this requires a separate investigation (Fried, 1978).

To determine with high accuracy the quantity of nutrients absorbed by wheat plants and to study the rhythm of nitrogen absorption during different phenophases, field experiments with ^{15}N labelled fertilizers in the framework of the Coordinated Research Programme by the Joint FAO/IAEA Division of Nuclear Techniques in Food and Agriculture were organized. Both nitrogen fertilizers – ammonium nitrate and urea – in rates of 120 kg N/ha were applied either all in autumn at seeding (A-treatment) or in split rates of 60 kg N/ha in autumn and 60 kg N/ha in spring, a case in which ^{15}N labelled fertilizer was applied on different plots (B-treatment, B1, B2). In treatment C, to study the rhythm of N absorption during the vegetation period of wheat, besides 20 kg N/ha applied in autumn, 100 kg N/ha was applied, namely: a - early in spring, at the third node; b - at the boot stage; c - at 50% heading; d -at 50% flowering; e - grain at milk stage. This C-treatment was divided into 5 sub-plots, each one receiving 20 kg N/ha, labelled with ^{15}N, only at one phenophase, the rest of the phenophases receiving unlabelled nitrogen fertilizer. In this way, it can be determined exactly how nitrogen derived from fertilizer is used in each phenophase, other factors being constant.

TABLE 1

Effect of applying 25 kg N/ha as ammonium sulphate to rice at four different growth stages on the % N in the grain derived from the fertilizer

Growth rate from the fertilizer applied[1] (kg N/ha)				% N derived from the ^{15}N labelled fertilizer			
T_1	T_2	T_3	T_4	Bangladesh	India	Sri Lanka	Thailand
25*	25	25	25	7.84	6.59	6.09	10.17
25	25*	25	25	2.99	4.69	3.12	10.34
25	25	25*	25	5.97	6.42	2.99	10.89
25	25	25	25*	8.29	11.79	6.42	17.82
			LSD (.05)	1.71	2.06	1.74	2.11

[1] T_1 = basal at transplanting
T_2 = 3 weeks after transplanting
T_3 = midway between T_2 and T_4
T_4 = primordial initiation

* labelled with ^{15}N

TABLE 2

Influence of different forms and times of application of the fertilizer on wheat yield

Treatments	Yield (100 kg/ha)					
	Kernel			Straw		
	NH_4NO_3	$(NH_2)_2CO$	$\bar{x}$	NH_4NO_3	$(NH_2)_2CO$	$\bar{x}$
A	33.5	39.4	36.5	108.5	94.5	101.5
B	40.2[1]	40.7	40.4[2]	113.4	118.8[2]	116.1[2]
C	38.3	36.7	37.5	116.3	110.0[2]	113.1[2]
LSD 5%	3.8	3.8	3.7	11.0	11.0	7.8

[1] Significant at 1% level
[2] Significant at 5% level

Of the two factors studied, namely the form of fertilizer – NH_4N0_3 or $(NH_2)_2CO$ – and the time of application, at the same quantity of active ingredient, the time of application had the strongest influence on kernel yield (Table 2). If, at kernel yield, the time of application influenced the efficiency of ammonium nitrate, at straw yield the differentiation, depending on the time of application, was stronger in the case of urea. The different effects in the case of the two forms of fertilizer, on kernel and straw yield, may be affected by the specific characteristics of the fertilizer-soil-plant interaction. During the first period of vegetation (up to heading), ammonium nitrate is utilized better than urea, the latter needing to be decomposed in the soil in the forms of NH_4^+ and $N0_3^-$. Owing to the formation of a larger vegetative mass, the lodging phenomenon was stressed, and as a result, kernel yield obtained from fertilizer applied at a rate of 120 kg N/ha, as ammonium nitrate, in autumn, was lower than the one obtained by the urea treatment. Also, the well known fact that $N0_3^-$ leaches below the active area of the root system must not be neglected (Hera, 1979b; Hera *et al.*, 1984).

The lower yield obtained with treatment C, in which a rate of 120 kg N/ha was applied in six stages, proves that plant needs were not satisfied with the low nitrogen rates distributed at different times.

TABLE 3

Influence of different forms and times of application of N-fertilizer on the N-utilization coefficient from fertilizer

Treatments		N content %	Absorbed N (kg/ha)	% Ndff	Absorbed N (kg/ha)		Utilization coefficient %
					from soil	from fertilizer	
In kernel:							
NH_4NO_3	A	2.29	76.7	39.6	46.3	30.4	25.3
	B1	-	-	18.6	-	17.6	29.3
	B2	-	-	24.5	-	23.1	38.5
	B	2.35	94.5	43.1	53.8	40.7	33.9
	C	2.35	90.0	36.4	57.2	32.8	32.8
$(NH_2)_2CO$	A	2.29	90.2	36.1	57.6	32.6	27.3
	B1	-	-	15.3	-	14.6	24.3
	B2	-	-	22.0	-	20.9	34.8
	B	2.34	95.2	37.3	59.7	35.5	29.6
	C	2.39	87.7	33.2	58.6	29.1	29.1
LSD 5%		0.125		3.5			
In straw:							
NH_4NO_3	A	0.66	71.6	36.8	45.3	26.3	21.9
	B1	-	-	23.2	-	18.1	30.2
	B2	-	-	20.5	-	16.0	26.7
	B	0.69	78.2	43.7	44.0	34.2	28.5
	C	0.79	91.9	25.5	68.5	23.4	23.4
$(NH_2)_2CO$	A	0.60	56.7	37.2	35.6	21.1	17.6
	B1	-	-	15.9	-	12.8	21.3
	B2	-	-	20.6	-	16.6	27.8
	B	0.68	80.8	36.5	51.3	29.5	24.5
	C	0.80	88.0	25.4	65.7	22.3	22.3
LSD 5%		0.14		3.0			

Nitrogen fertilizer influenced the grain quality in a positive way, i.e. by increasing the protein content of the kernel. As a result, an increase in the total nitrogen output by the yield was noted, as a function of form and time of fertilizer application. Of the amount of N taken by the kernels, 33 - 34% is derived from fertilizer. The highest % Ndff values were obtained when half of the total nitrogen rate was applied in autumn and the other half early in spring (Table 3). The coefficient of utilization of N coming from fertilizer in kernel and straw ranges from 47.2% to 62.4% in the case of ammonium nitrate and from 44.9% to 54.1% in the case of urea, depending on the time of application. The highest utilization coefficient was noticed in the case of a split application – 60 kg N/ha in autumn and 60 kg N/ha in spring with an increase of 15.2% in the case of NH_4N0_3 and 9.5% in the case of $(NH_2)_2CO$ (Hera, 1979b).

For good kernel formation, wheat needs a good nitrogen supply when 50% of the plants are at flowering. From the nitrogen applied as fertilizer, up to this phenophase, over 50% is used with a maximum of 69.8%, when the fertilizer is applied at 50% heading stage of the plants (Table 4). It follows that, to obtain wheat yields that are superior quantitatively and

TABLE 4
Influence of different times of application on the N-uptake from fertilizer

Fertilizer application at stage: (C-treatment)	Kernel						Straw						Total		
	% Ndff			Utilization coefficient			% Ndff			Utilization coefficient			Utilization coefficient		
	I	II	$\overline{x}$	I	II	$\overline{x}$	I	II	$\overline{x}$	I	II	$\overline{x}$	I	II	$\overline{x}$
a. In spring at the 3rd node	7.2	5.4	6.3	32.4	23.7	28.0	6.5	5.0	5.7	29.9	22.0	25.9	62.3	45.7	50.4
b. Boot stage	7.0	5.4	6.2	31.5	23.7	27.6	4.9	6.1	5.5	22.5	26.8	24.7	54.0	50.5	52.2
c. At 50% heading	9.6	9.9	9.7	43.2	43.4	43.3	5.9	5.9	5.9	27.1	26.0	26.5	70.3	69.4	69.8
d. At 50% flowering	8.6	9.4	9.0	38.7	41.2	39.9	4.3	3.9	4.1	19.7	17.2	18.4	58.5	58.4	58.4
e. Kernel milk stage	4.0	3.1	3.5	18.0	13.6	15.8	3.8	4.6	4.2	17.5	20.2	18.8	35.5	33.8	34.6

I. NH_4NO_3 II. $(NH_2)_2CO$

TABLE 5
Nitrogen uptake from NO_3^- and NH_4^+ from ammonium nitrate

Time and rate of N application (kg/ha)		Kernel			Straw			Total		
Autumn	Spring	% Ndff	N absorbed from fertilizer kg/ha	Utilization coefficient %	% Ndff	N absorbed from fertilizer kg/ha	Utilization coefficient %	% Ndff	N absorbed from fertilizer kg/ha	Utilization coefficient %
$^{15}NH_4NO_3$										
60*	60	8.0	7.6	25.3	7.9	6.1	20.3	15.9	13.7	45.6
60	60*	10.4	9.82	32.7	9.0	7.0	23.3	19.4	16.8	56.0
Total		18.4	17.4	29.0	16.9	13.1	21.8	35.3	30.5	50.8
$NH_4{}^{15}NO_3$										
60*	60	10.2	9.6	32.0	10.6	8.3	27.7	20.8	17.9	59.7
60	60*	12.0	11.3	37.7	13.0	10.2	34.0	25.0	21.5	71.7
Total		22.2	20.9	34.8	23.6	18.5	30.8	45.8	39.4	65.6

* Labelled with ^{15}N

qualitatively, a good nitrogen supply for the plants is needed during almost the whole vegetation period, the first phases being decisive as regards the quantity, and the heading-flowering stages as regards the quality.

Of the two forms of application studied, a small difference was noticed in favour of NH_4N0_3, especially at fertilization at the third node stage and at the boot stage (Hera, 1979b; Hera *et al.*, 1984).

These results show a preferential absorption function of the chemical composition of the fertilizers and of the ions which play a role in nitrogen plant nutrition. To determine the respective contribution of NH_4^+ and $N0_3^-$ ion in nutrition, depending on the time of application and on the soil-plant interaction, by means of NH_4N0_3 labelled with ^{15}N, the contribution of the two ions NH_4^+ and $N0_3^-$ applied as fertilizers at the time of grain formation was studied.

Thus, from the total of 120 kg N/ha applied half in autumn and half in spring, NH_4^+ accounts for 29% at kernel formation, and 21.8% at straw formation, the general utilization coefficient being 50.8%.

In the same conditions, the nitrate form was more efficient, the utilization coefficient being 34.8% for kernel, 30.8% for straw, the total being 65.6% (Table 5).

The higher contribution of the $N0_3^-$ at the time of grain formation indicated by% Ndff, the utilization coefficient being higher in all cases, may be caused by the higher mobility of this ion. It is known that, in contrast to the NH_4^+ ion, the $N0_3^-$ ion is retained to a much lesser extent by the soil adsorptive complex, circulating in the soil solution by mass flow. The fact that the nitrate moves with the water allows the root system to exploit the nitrate ion better. This can explain the superior values of the utilization coefficient of $N0_3^-$ (Hera *et al.*, 1984).

Some interesting results have been obtained on soybean (Table 6). The only significant yield increases were obtained when the amount of 30 kg N/ha was applied during vegetation period, before flowering. In this case, %Ndff was 3.2% and the utilization coefficient of N was 20.2%. The highest N content in soybean seeds, derived from soil and symbiotic activity was obtained also when 30 kg N/ha was applied before flowering, which means that the symbiotic process of N_2 fixation took place in optimum conditions. When the intensity of symbiotic activity begins to diminish, the application of low rates of nitrogen fertilizer before flowering stage of soybean can lead to significant yield increases (Hera *et al.*, 1984).

Assessment of nutrient availability as a function of different methods of fertilizer application

Among the factors affecting crop production, fertilizer placement plays an important role. A strong argument in favour of this affirmation are the results received from five countries which participated in the first Coordinated Research Programme organized by the Agriculture Unit of the International Atomic Energy Agency on Rice Fertilization (Table 7).

Surface application and hoeing into the surface were equally effective. At all locations, all other treatments were less effective in supplying fertilizer phosphorus to the rice plant (Fried, 1978; IAEA, 1978). This was in spite of the fact that placement at 10 cm depth in the planting hill actually involved placing the fertilizer in the hole in which the rice plant was transplanted, a treatment that most of the participants and observers anticipated would be the most effective treatment. Before the field experiments with ^{32}P labelled superphosphate were performed, the five-year programme with the non-labelled fertilizer had given inconclusive results and the debate concerned the desirability of extending the programme for another five years. In only a one-year experiment with radioactive labelled fertilizers, the participating countries in the programme had answered the questions.

TABLE 6
Influence of time and rate of N-fertilizer on yield and nitrogen uptake by soybeans

Treatments		Yield (100 kg/ha) dm	N content %	% Ndff	Absorbed N (kg/ha)			Utilization coefficient %
$\frac{P}{N}$	$\frac{V}{N}$				From soil and symbiosis	From fertilizer	Total	
0	0	32.6	5.40	-	176.0	-	176	-
30	0	32.7	5.55	7.7	168.0	14.0	182	46.6
0	0	31.1	5.21	-	162.0	-	162	-
30	0	30.2	5.25	6.0	149.5	9.5	159	31.7
60	0	31.1	5.18	15.8	135.5	25.5	161	42.4
90	0	30.2	5.28	24.7	120.6	39.4	160	43.8
0	30	33.6	5.63	3.2	182.9	6.1	189	20.2
0	60	32.9	5.75	8.5	173.0	16.0	189	26.7
30	30	31.1	5.34	11.0	147.7	18.3	166	30.4
30	60	32.6	5.30	15.8	145.7	27.3	173	30.3
LSD 5%		0.9	0.25					

P = at planting V = during vegetation dm = dry matter

TABLE 7
Effect of placement on the % of P in rice plants that was derived from fertilizers

Location	Treatments						LS 5%
	Surface	Hoeing	Hill 10[1]	Hill 20	Row 10[2]	Row 20	
Philippines (Los Baños)	17	17	6	4	4	3	2
Thailand (Bankhen)	68	68	50	34	51	36	9
Thailand (Surin)	37	40	22	15	26	23	2
Myanmar (Cyogon)	11	17	6	4	4	3	2
Myanmar (Mandalay)	25	25	6	6	6	4	3
Pakistan (Tandojam)	48	50	5	4	4	4	5
Egypt (Sakha)	64	60	37	38	38	37	10

[1] Placement at 10 cm depth in the planting hill.

[2] Placement at 10 cm depth between the rice rows.

The placement of nitrogen fertilizer also influenced to a great extent the yield and nitrogen uptake by the plants (Table 8). By applying 80 kg N/ha in bands at seeding and 80 kg N/ha side-dressing, it was observed during the vegetation period that there was a yield increase with 620 kg/ha of maize kernels and an increase in the coefficient of utilization of N coming from fertilizer from 41.8% to 61.1% in comparison with the application of 80 kg N/ha broadcasting and plough-down and 80 kg N/ha in bands at seeding. Placement of 80 kg N/ha in bands at seeding and 80 kg/ha side-dressing at vegetation, in comparison with 80 kg N/ha broadcasting and ploughed-down and 80 kg N/ha side-dressing at vegetation, also resulted in the cost reduction, as the work was done simultaneously with seeding and weeding, by adding to the seeders and cultivator machines the required equipment for fertilizer application (Hera, 1979a).

Regarding the good results obtained in the field experiment with ^{15}N labelled fertilizers in Romania, the new method of fertilizer placement was extended on an area of 2 000 000 ha planted with maize. The results are presented in Figure 1. The figure highlights the 6 years average yield increase of 620 kg/ha kernels obtained in research and production as compared to those obtained through the classical method of broadcast application of fertilizers. The investment made for adapting the seeders and the cultivators to the new methods of fertilizer application represents only 5% of the total value of the yield increase that can be obtained every year. The advantage of the new method is obvious if consideration is given to the elimination of the supplementary work in applying the fertilizer in the classical method, and as a result, the diminution of the fuel consumption and the elimination of the possibilities of worsening the physical soil characteristics by supplementary soil operations. Translating the obtained maize yield increase into tonnes of meat, it can be said that 207 000 additional tonnes of meat can be produced every year (Figure 1) (Hera, 1979b).

Some very interesting results were received by Zaharah *et al.* (1989) on fertilizer placement studies in mature oil palm, using isotope techniques. Mature oil palms were found to be able to absorb ^{32}P applied to the soil from as far as 36 m away from the point of application, thus proving that their roots were well distributed throughout the area.

Foliar application of fertilizer

A clear distinction between root and non-root absorbed nutrients occurring simultaneously in the plants can be made by the use of isotopes. Datta and Vyas (1967) carried out an evaluation of the magnitude of the nutritional contribution of a number of foliar-applied phosphate fertilizers labelled with ^{32}P. Results obtained in New Delhi, India, on the uptake by maize of total and fertilizer phosphorus and percentage utilization of the applied fertilizer at the equivalent doses of 5.6 kg P_2O_5/ha of superphosphate, monocalcium phosphate, dicalcium phosphate and ammonium phosphate through foliar and soil application at three stages of growth [24 (I), 39 (II) and 60 (III) days after germination] are presented in Table 9.

From the results presented in Table 9, it can be seen that the total uptake of phosphorus from foliar application was significantly superior compared with soil application at all stages of growth. In the data on percent fertilizer phosphorus uptake it is observed that foliar application was eight and two times as efficient as soil application at the first and second stage respectively. It was also superior at the third stage. Percent utilization of the fertilizer phosphorus from foliar application was nearly six times as efficient as soil application in the

TABLE 8
Nitrogen utilization by maize depending on the fertilizer placement

Fertilizer (as NH_4NO_3 placement)	Average yield[a]		N-consumption from the fertilizer (kg/ha)			N-consumption from the fertilizer (kg/ha)			
	Grains q/ha	Stalks q/ha	Grains	Stalks	Total	Grains	Stalks	Total	Fertilizer utilization rate[b] %
I	92.6	82.0	135.2	44.9	180.1	46.8	14.3	61.1	38.2
II	86.4	80.6	127.9	48.1	176.0	28.8	13.0	41.8	26.1
LSD 5%	5.8	9.8	7.0	3.5		5.1	2.7		

Fertilizer (as NH_4NO_3 placement)	Distribution of the N-consumption from the fertilizer at various times and methods of application FERTILIZER PLACEMENT											
	PLOUGH - DOWN (BROADCASTING)				BAND - APPLICATION (AT SEEDING)				SIDE - DRESSING (DURING THE VEGETATION PERIOD)			
	in Grain kg/ha	in Stalk kg/ha	Total kg/ha	fertilizer utilization rate %	in Grain kg/ha	in Stalk kg/ha	Total kg/ha	fertilizer utilization [c] rate %	in Grain kg/ha	in Stalk kg/ha	Total kg/ha	fertilizer utilization rate %
I	-	-	-	-	12.8	6.7	19.5	24.3	34.0	7.6	41.6	52.0
II	16.0	6.3	22.3	27.8	12.8	6.7	19.5	24.3	-	-	-	-

a) Calculated at 15.5% moisture content in grains and 0 (zero) in stalks

b) Reported for 160 kg N/ha

c) Reported for 80 kg N/ha

TABLE 9

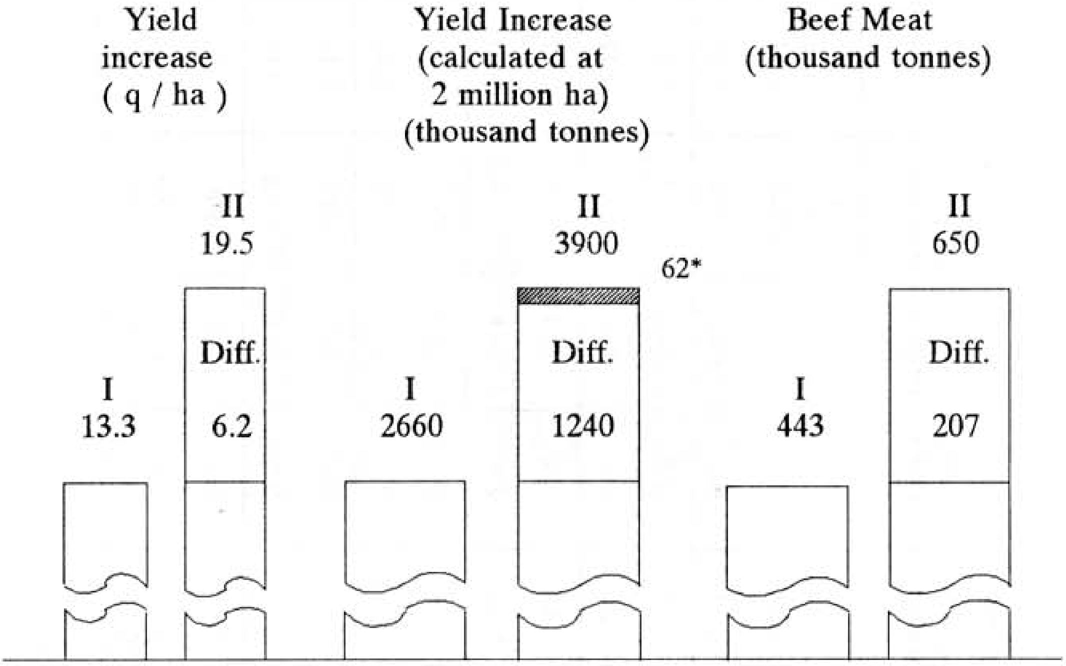
Uptake of phosphorus from different sources at different stages of growth

(Datta and Vyas 1967)

Treatment		Uptake of total P in mg/g plant material			Uptake of fertilizer phosphorus (%)			Utilization of fertilizer (%)		
Stage	Application	I	II	III	I	II	III	I	II	III
Super-phosphate	Spray	0.89	1.04	1.33	40.0	40.7	13.8	0.54	0.76	1.07
	Soil	0.90	1.00	1.08	4.6	15.2	10.2	0.08	0.34	1.85
Mono-calcium phosphate	Spray	1.06	1.19	1.49	27.5	30.9	17.3	1.61	1.84	4.20
	Soil	1.07	1.19	1.24	3.2	15.9	12.2	0.27	2.20	5.50
Dicalcium phosphate	Spray	0.88	0.94	1.42	29.2	35.6	24.7	0.87	1.00	2.10
	Soil	0.45	0.50	1.30	2.6	14.1	12.5	0.03	0.90	3.60
Ammonium phosphate	Spray	1.02	0.90	1.34	32.6	56.0	22.2	1.83	2.70	4.80
	Soil	0.45	1.40	1.10	3.4	18.3	10.4	0.40	2.50	5.80
Average	Spray	0.94	1.3	1.4	30.6	40.8	19.5	1.20	1.6	3.0
	Soil	0.74	1.0	1.2	3.5	15.9	11.3	0.19	1.5	4.2
F-test (application)		Sig.[a]	Sig.	Sig.	Sig.	Sig.	Sig.	Sig.	Not sig.	Sig.
S.E.$_{m}$. ±		0.03	0.06	0.05	1.8	1.03	1.07	0.06	1.15	0.26
C.D. @ 5%		0.09	0.24	0.16	5.2	2.96	3.08	0.19	--	0.82

a) Sig. = Significant

FIGURE 1
Advantage of using the method of application of N and P fertilizer at seeding in bands (II) as compared with the broadcast application (I). The figure of 62 000 tonnes (marked with an asterisk) represents the value of the investment made in bringing in the new method (q = metric quintal = 100 kg)



early stage. In the later stages of growth, however, there were not large differences in the utilization.

Foliar application increased the percentage uptake of fertilizer phosphorus (Datta and Vyas, 1967). It was observed that at early stages of growth, foliar application was not only superior to the equivalent rate of soil application but also higher than 22.4 and 89.7 kg P_2O_5/ha. Phosphorus is needed by the plants at the early stages of growth and if they do not get sufficient phosphorus at the early stages, then they cannot extract phosphorus efficiently in the later stages. Thus, higher uptake of phosphorus through foliar application at early stages could be attributed firstly to the young and expanding leaves which are active and secondly to the still largely undeveloped root system.

Nitrogen fertilizer can be also successfully used in foliar applications. The results received in Romania (Hera, 1979a) applying 33.5 kg N/ha at tasselling stage of growth by sprinkler irrigation, using a normal maize hybrid, HS 330, and an opaque hybrid, HS 335, showed not only yield increases but also an increase in the lysine yield per hectare (Figures 2 and 3).

FIGURE 2
Nitrogen fertilizer application on maize with irrigation water by sprinkling (q = metric quintal = 100 kg)

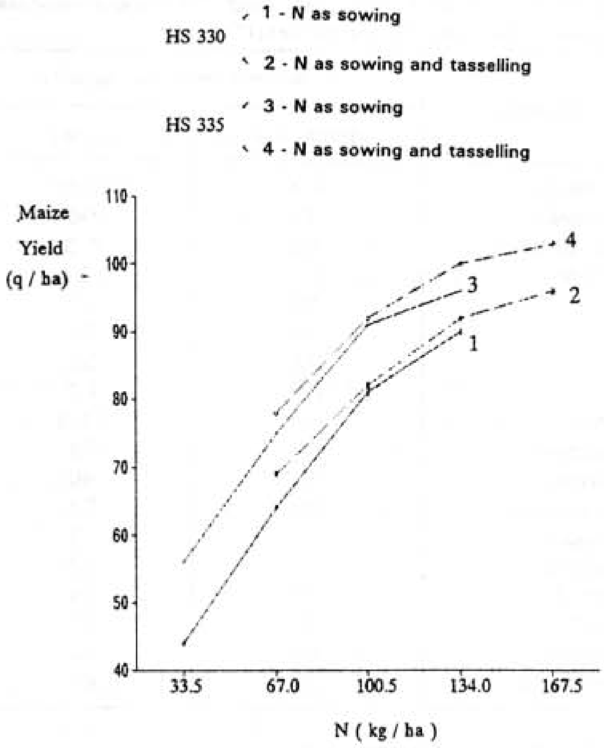


FIGURE 3
Influence of sprinkling fertilizer application on lysine production

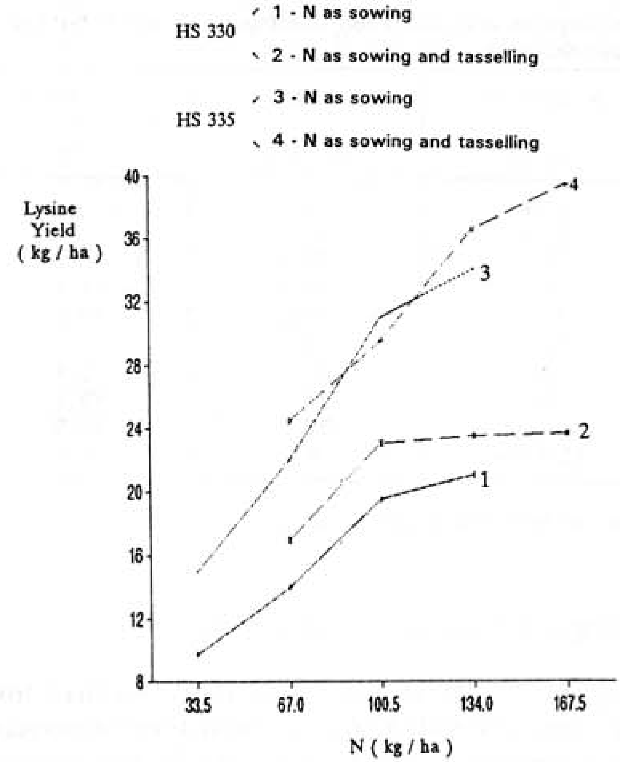


TABLE 10

Effect of mixing of $(^{15}NH_4)_2SO_4$ and ^{32}P superphosphate on the uptake of fertilizer nitrogen and phosphorus by rice (60 day harvest)*

Location	% P derived from the fertilizer		% N derived from the fertilizer	
	separated	mixed	separated	mixed
Myanmar	4.4	5.0	23	28
Sri Lanka	38	50	32	36
Rep. of China	5.8	6.5	27	27
Hungary	7.5	13.5	48	52
India I	10	17	44	47
India II	44	60	46	36
Italy	22	36	15	20
Korea I	7.8	7.2	50	49
Korea II	9.8	11.5	26	22
Madagascar	67	75	40	37
Pakistan	40	40	33	36
Bangladesh	56	53	20	22
Philippines	8	15	31	28
Thailand	72	82	28	30
Egypt I	18	34	25	25
Egypt II	20	27	33	33
Romania I	12	19	34	39
Romania II	28	47	43	52

* applied in rows at 5 cm depth.

TABLE 11

N absorption and utilization coefficient of the N-fertilizer, by sunflower, as a function of the NP-application rate

N and P_2O_5 (kg/ha)	Yield (100 kg/ha)	Absorbed N (kg/ha)		Utilization coefficient (%)
		Total	From fertilizer	
P_0N_0	28.9	-	-	-
$P_{30}N_0$	30.4	-	-	-
N_{40}	33.3	75.2	15.3	38.2
N_{80}	34.6	81.7	29.1	36.3
N_{120}	36.8	87.9	46.1	38.4
$P_{60}N_0$	29.7	-	-	-
N_{40}	34.6	75.4	18.3	45.7
N_{30}	36.8	88.3	33.9	42.3
N_{120}	36.6	95.9	51.3	42.7
LSD 5%	2.3	5.4	3.7	3.9

* As NH_4NO_3 and superphosphate.

Nitrogen x phosphorus interaction

Hera *et al.* (1984) reported many results received from field experiments, when ammonium salt, especially $(NH_4)_2SO_4$, was mixed with superphosphate. This led to a better utilization of the fertilizer phosphate than when the two fertilizers were applied separately. However, different results were received where nitrate salt was the source of nitrogen. This observation was further extended by means of an international coordinated programme on the efficiency of fertilizer use by maize where the question was examined at eighteen different locations adding the additional question of the effect of mixing the fertilizers on the uptake of fertilizer nitrogen (Fried, 1978; IAEA, 1970a). These questions could be quantitatively answered in a field experiment by labelling the superphosphate with ^{32}P and the nitrogen source with ^{15}N. Some of the results from this experiments are presented in Table 10. The results confirmed the observation that when $(NH_4)_2S0_4$ was mixed with superphosphate, the plants took up appreciably more of the phosphorus from the superphosphate. On the other hand, the same mixing had no continuous effect on the uptake of fertilizer nitrogen from the $(NH_4)_2S0_4$ source.

The results of earlier research on sunflowers had underlined the reduced effect of fertilizers on this crop, as on other crops, although the sunflower is a big consumer of nutrients. This is due mainly to the high capacity of its root system to absorb nutritive elements in less soluble forms from the soil (Hera, 1979b; IAEA, 1970a). In order to determine with precision the utilization coefficient of fertilizers with this crop, a number of experiments were conducted at the Research Institute for Cereals and Industrial Crops, Fundulea, Romania, using labelled fertilizers. Some of the results are presented in Table 11.

Mixed applications of N and P fertilizers elicited a significant yield increase, which reached 790 kg kernels per hectare, as compared with the non-fertilized control. The interaction of nitrogen fertilizer with phosphorus fertilizer made an important contribution to the yield increases. The amount of nitrogen absorbed by the sunflower seeds from the fertilizer determined with ^{15}N increased as the rate of N fertilizer increased. The utilization coefficient of nitrogen derived from the fertilizer ranged between 36.3% to 45.7%, this being negligibly influenced by the increases in the nitrogen fertilizer rate. The utilization coefficient of the nitrogen from fertilizer was significantly influenced by the levels of P fertilizer.

Biological nitrogen fixation

The Soil Fertility, Irrigation and Crop Production Section of the Joint FAO/IAEA Division has coordinated international programmes on biological nitrogen fixation in developing countries for more than two decades. The main objectives of these programmes were to develop and optimize the ^{15}N isotope dilution method to quantify N_2 fixation in leguminous crops and to enhance nitrogen fixation in various cropping systems.

Great emphasis has been placed on biological nitrogen fixation by the FAO/IAEA due to the importance of this process in developing countries and the unique use of ^{15}N to quantify N_2 fixation. Most of this work has been performed in Coordinated Research Programmes (CRP) or Technical Cooperation Projects (TCP). Table 12 shows previous and present programmes on biological nitrogen fixation as well as the number of participating countries.

The initial programmes on nitrogen fixation focused on grain legumes and the development of ^{15}N methodology. These programmes were later followed by others quantifying biological nitrogen fixation in forage or pasture legumes, *Azolla* and tree legumes. The most recent programmes emphasize the enhancement of nitrogen fixation in some grain legume species.

TABLE 12
Coordinated Research Programmes on biological nitrogen fixation which have been conducted by the Soil Fertility, Irrigation and Crop Production Section of the Joint FAO/IAEA Division

Programme Short Title	Duration	No. of participating countries
A Fertilization of grain legumes	1972 - 1977	13
B Grain legumes[1]	1979 - 1983	19
C Multiple cropping	1980 - 1985	9
D Pasture[2]	1983 - 1988	19
E Azolla[1]	1984 - 1989	13
F Common bean in Latin America	1986 - 1991	7
G Grain legumes in Asia[3]	1987 - (1993)	10
H Tree legumes	1989 - (1993)	15
I Microbial ecology	1992 - (1997)	11

[1] Funded by the Swedish International Development Authority
[2] Funded by the Government of Italy
[3] Funded by the United Nations Development Programme

As an example, two FAO/IAEA Coordinated Research Programmes will be mentioned: one interregional on *Azolla*, the other on common bean (*Phaseolus vulgaris L.*) in Latin America which have recently been finished and the results published (Bliss and Hardarson, 1993; Kumarasinghe and Eskew, 1993).

Azolla

The first Coordinated Research Programme on *Azolla* was conducted during the five-year period 1984-1989.

The economic and environmental costs of the heavy use of industry-made N fertilizers in agriculture have now become global problems. Alternatives to the use of commercial N fertilizers must therefore be sought if crop production is to be sustained. Plant species such as *Azolla* in symbiosis with the blue-green algae *Anabaena azollae* are capable of fixing atmospheric N_2. Such nitrogen fixing systems offer an attractive and ecologically sound means of reducing external inputs of chemical N fertilizers in cropping systems.

Azolla is a free-floating water fern widely distributed in aquatic habitats of the tropics and sub-tropics. Because of its aquatic nature, *Azolla* is of particular value to flooded rice. Several methods have been used to estimate biological N_2 fixation of *Azolla*. Quantitative integrated values for biological N_2 fixation by *Azolla* have been obtained through the use of the ^{15}N isotope. *Azolla* can derive as much as 70-80% of its N from N_2 fixation, yielding 22-24 kg N/ha in about one month. However, differences in N_2 fixation are common depending on the *Azolla* species or strain and the environmental conditions. In this research programme,

^{15}N was also used as a tracer to assess the N recovery by rice from *Azolla* and N balance in the rice cropping system (Figure 4). Incorporation of ^{15}N labelled *Azolla* into soil gave an ^{15}N recovery by rice of 40-50%. On an overall basis under a wide range of environmental and soil conditions in six countries, the ^{15}N recovery from *Azolla* was not very different from that of urea (Figure 5). The general conclusion from this programme is that *Azolla* is as good as urea as a source of N for rice. In addition, the results of this programme have revealed that an *Azolla* cover over the floodwater can increase the fertilizer use efficiency of applied urea and consequently, the rice yield (Kumarasinghe and Eskew, 1993). Rice occupies about 90% of the area under cereals in the Asia and Pacific region. Research aimed at developing improved integrated fertilizer management practices involving the use of green manures such as *Azolla* with reduced inputs of chemical fertilizers, is very much needed. Intensive efforts are also necessary to take the results of agronomic research to the farmers so that the impacts of *Azolla* use in sustainable rice production may become more visible (Kumarasinghe and Eskew, 1993).

Common bean

The second FAO/IAEA Coordinated Research Programme was on common bean in Latin America. Field experiments were performed in Brazil, Chile, Guatemala, Mexico, Peru and by the FAO/IAEA in Austria, to investigate nitrogen fixation potential of cultivars and breeding lines of common bean. Each experiment included approximately 20 bean genotypes which were compared using the ^{15}N isotope dilution method. As an example, Figures 6 and 7 show the% Ndfa and amounts of N_2 fixed when 29 common bean cultivars were tested at the FAO/IAEA Seibersdorf Laboratory in Austria. In this experiment, the range of fixation was from 37 to 67% or 20 to 165 kg N/ha. Similar results were obtained at Irapuato in Mexico, where %Ndfa ranged from 4 to 65% when tested in 20 cultivars (Figure 8).

When N_2 fixation was tested in all the participating countries, great differences in nitrogen fixation were observed between and within experiments, with average values of 35% N derived from atmosphere (% Ndfa) and highest values of 70% Ndfa being observed (Figure 9). Some of the best cultivars were also found to be more effective in biological nitrogen fixation than the commercial cultivars tested (Table 13). However, these larger values which had been reported previously for common bean, were observed only when environmental factors were favourable. Therefore, common bean lines are available, which can support high biological nitrogen fixation. These can be used either directly as cultivars for production or in breeding programmes to enhance nitrogen fixation in other cultivars. If these results were applied by farmers in Latin America, they could increase biological nitrogen fixation by common bean by at least 10-20%, which is equivalent to about 10-20 kg N/ha. One would have to apply 30-60 kg N/ha as fertilizer to receive the same amount of N in the crop. This increase would be of great economic importance (Bliss and Hardarson 1993).

Leaching and nutrients recovery

Under intensive agriculture, with high rates of nitrogen fertilizer, there is a major concern for a potential contamination of groundwater by $N0_3^-$ not taken up by the crops, which may move to various depths in the soil and enter the groundwater depending on rainfall or irrigation conditions and various soil properties.

FIGURE 4

Comparison in six countries of ^{15}N recovery from ^{15}N labelled *Azolla* applied at transplanting and unlabelled *Azolla* at maximum tillering (AZ* + AZ), unlabelled *Azolla* applied at transplanting and ^{15}N labelled *Azolla* at maximum tillering (AZ + AZ*), ^{15}N labelled urea applied at transplanting and unlabelled urea at maximum tillering (U* + U), unlabelled urea applied at transplanting and ^{15}N labelled urea at maximum tillering (U + U*), and urea best split (U - BS)

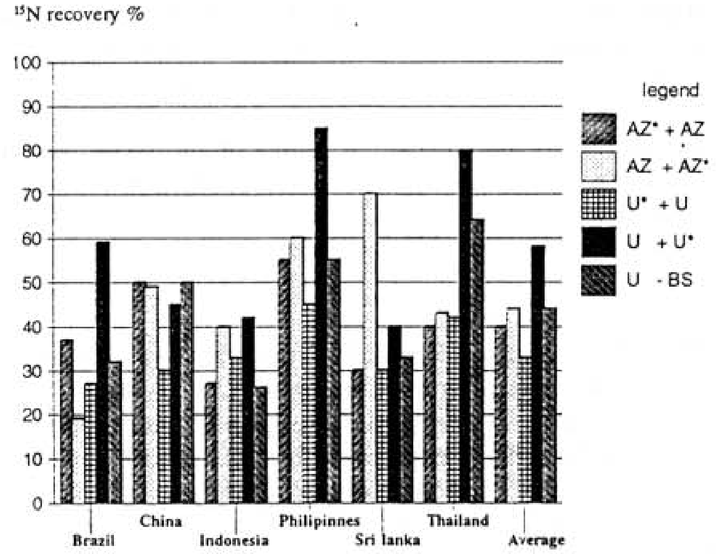


FIGURE 5

Comparison of panicle dry matter yield applied *Azolla*, urea, urea best split for the country, and the control

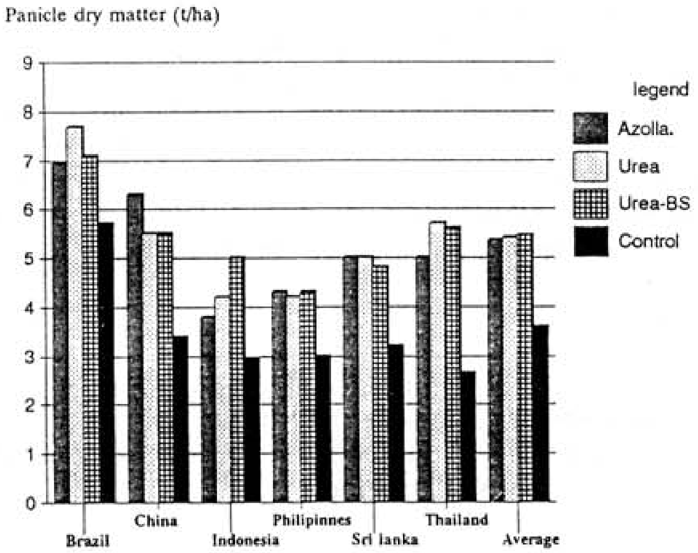


FIGURE 6
Percent N derived from atmosphere in 29 lines of *Phaseolus vulgaris*

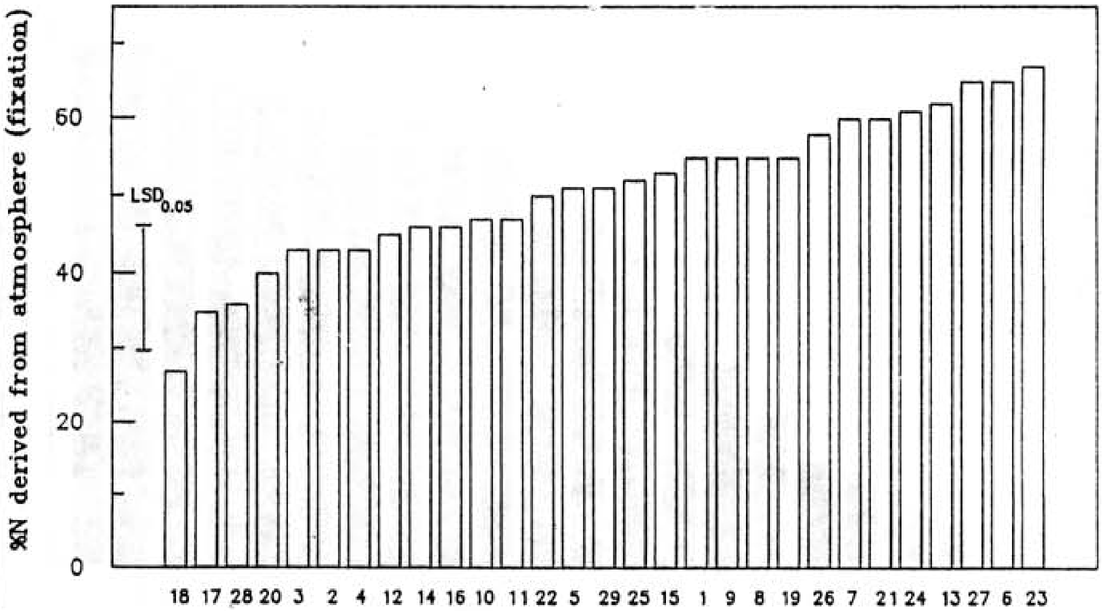


FIGURE 7
Amount of N (kg/ha) derived from air by 29 *Phaseolus vulgaris* lines

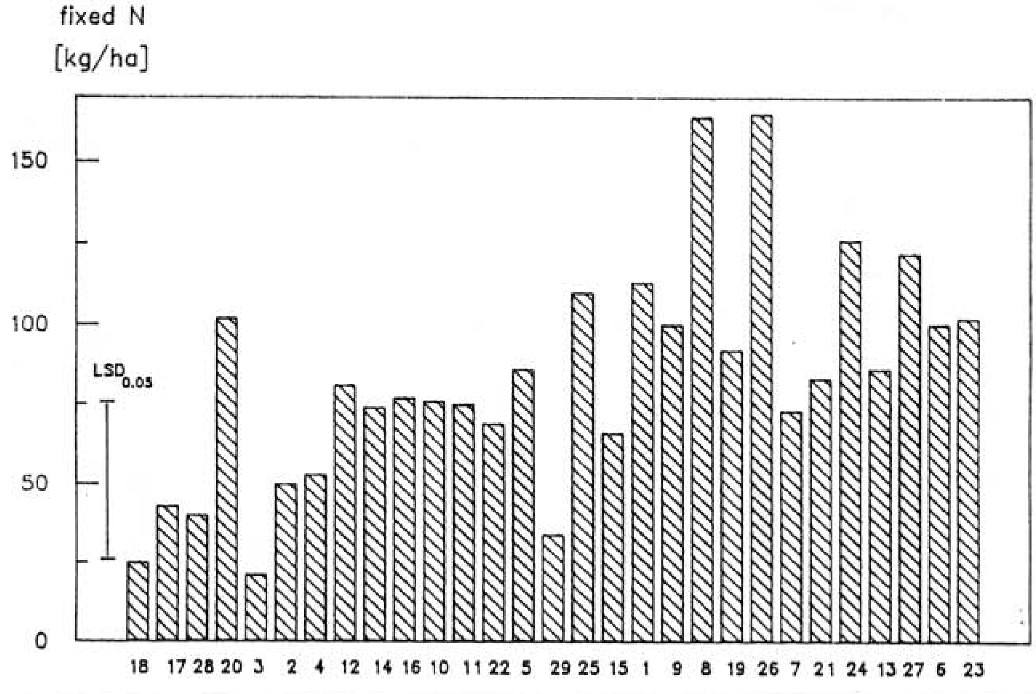


FIGURE 8

Differences in biological nitrogen fixation (%) between common bean cultivars as measured by the ^{15}N isotope (experiment conducted in Mexico by Dr. J. Peña-Cabriales)

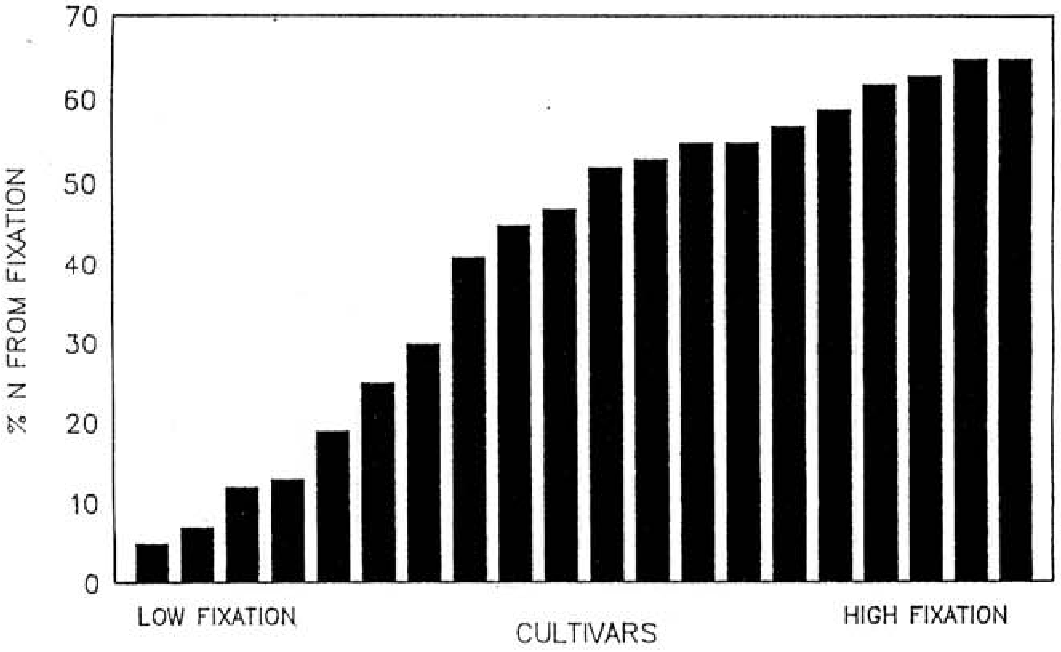


FIGURE 9

Percentage N derived from atmosphere (% Ndfa) of cultivars having the lowest and highest nitrogen fixation rates

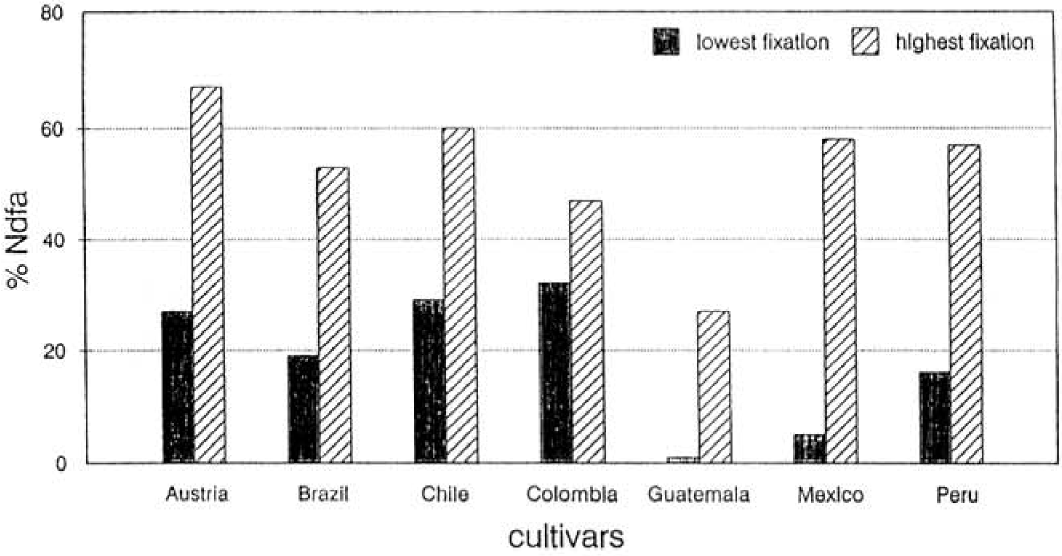


TABLE 13
Nitrogen fixation of some commercial cultivars in comparison to the best ones tested in each trial

Commercial cultivar				Best cultivar		
Location	Cultivar	% Ndfa	Amount kg N/ha	Cultivar	% Ndfa	Amount kg N/ha
Chile '87	Tortola	44	50	Araucano	52	61
Chile '88	Tortola	52	90	Araucano	59	115
Mexico	Flor de Mayo	51	89	WB 21-58	55	108
Peru '87	Canario	54	42	Caballero	57	59
Peru '88	Canario	40	26	Caballero	54	71

In order to study what would happen to the N unused by the main and secondary crop yield, an experiment with labelled ammonium nitrate was undertaken on irrigation conditions at Fundulea Research Institute for Cereals and Industrial Crops to determine the quantity of the N leached in the soil and that recovered by silo maize crop, seeded immediately after harvesting the wheat. For a 120 kg N/ha rate, about 16 kg N/ha were found at 80 cm depth, and for a 240 kg N/ha rate, about 28 kg N/ha were at 110 cm depth, the quantity leached N decreasing with depth of profile, though N derived from the fertilizer can still be found at the depth of 200 cm (Figure 10). A part of the N leached in the soil was recovered by the maize crop seeded immediately after harvesting the wheat (Figure 11).

Some studies on the assessment of P from phosphate rock

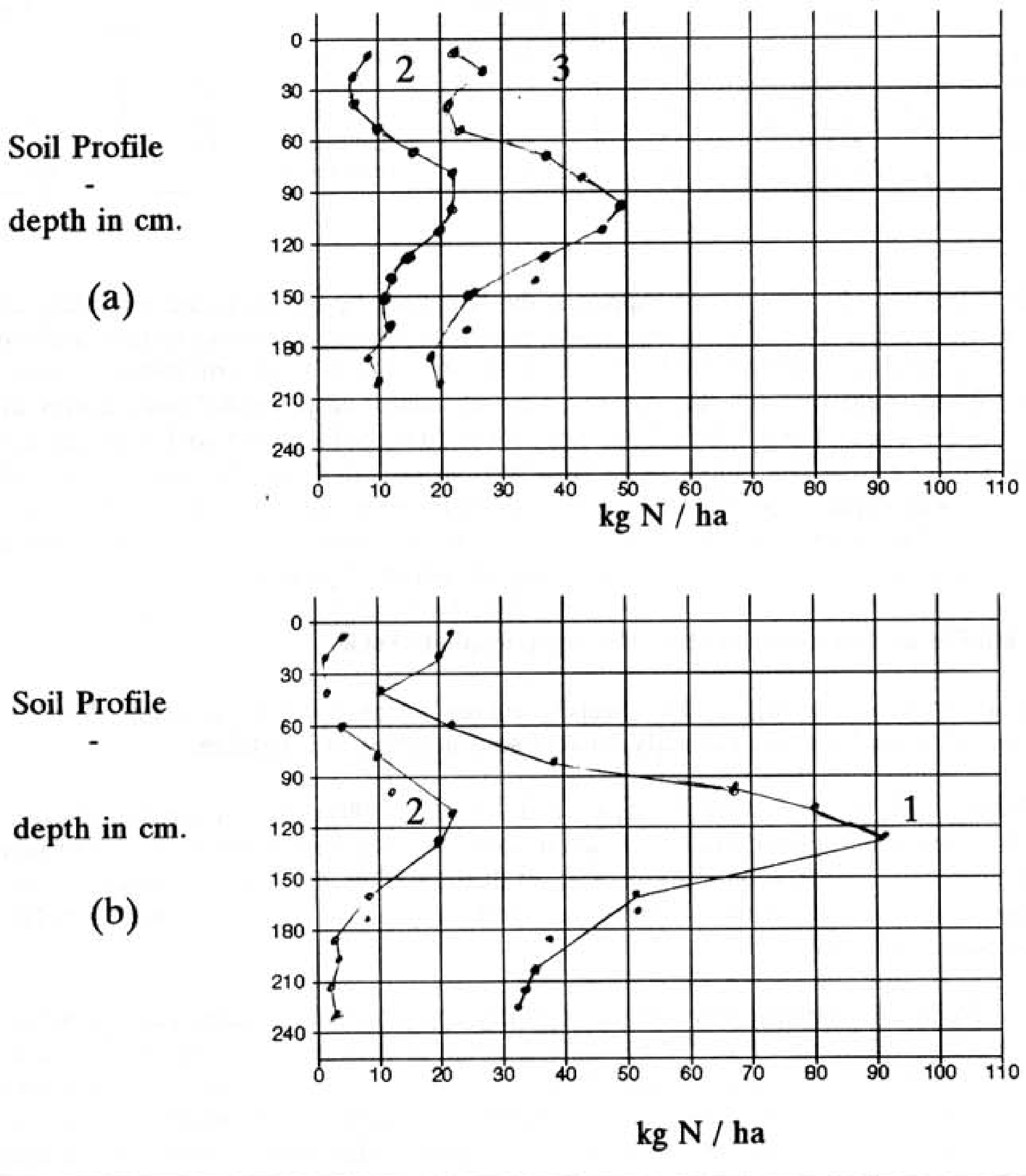
Phosphate rock is considered the cheapest source of phosphorus in many developing countries, if it can be applied directly on acid soils as phosphate fertilizer.

Truong Binh *et al.* (quoted in Zapata and Axmann, 1991) pointed out that the use of rock phosphate materials for direct applications to crops in the field depends on both technical and economical considerations. Agronomic evaluation trials need to be conducted under greenhouse and field conditions to obtain basic information on the ability of these sources to provide phosphorus on crops.

The IAEA Seibersdorf Laboratory is routinely applying isotope techniques by means of the radioactive tracers as ^{32}P or ^{33}P for the evaluation of rock phosphate in connection with field projects of the FAO Plant Nutrition Programme. Zapata and Axmann (1991) studied the agronomic effectiveness by means of ^{32}P tracer techniques of the suitability for direct application of 14 rock phosphates from different regions. The main objective was to assess the plant-available amount of phosphorus supplied by these materials and to determine the agronomic effectiveness of these rock phosphates in terms of equivalent units of ordinary superphosphate. A summary of the results is presented in Table 14 and Figure 12.

Zapata and Axmann (1991) concluded that the use of the ^{32}P radiotracer technique proved to be a very valuable tool in the agronomic evaluation test of rock phosphate effectiveness. The half rate application, i.e. 1000 mg P/pot or 500 ppm P for the various rock phosphate materials, was found to be sufficient for tests using isotopic techniques. Greenhouse trials have so far provided preliminary information on the suitability of rock phosphate materials for direct application to crops. This information is essential for the

FIGURE 10
Distribution of total NO_3 (1) and fertilizer NO_3 (2) on chernozium soil profile at Fundulea, in the treatments with 120 (a) and 240 (b) kg N/ha



establishment of field evaluation trials in various locations of interest. Long-term field experiments to obtain information on P availability over a longer period of time would be necessary. Zaharah and Sharifuddin (1990) found that the effectiveness of tested rock phosphate is variable as compared to superphosphate, when measured 30 days after planting. However, these rock phosphates were three to five times more effective than triple superphosphate in the second cropping. Very good results were obtained by Hera *et al.*, (1984) with North Carolina Rock Phosphate (NCRP). On soils with pH 4-5, the yield

FIGURE 11
Nitrogen utilization coefficient (NUC in %) in wheat as a main crop and maize as a second crop

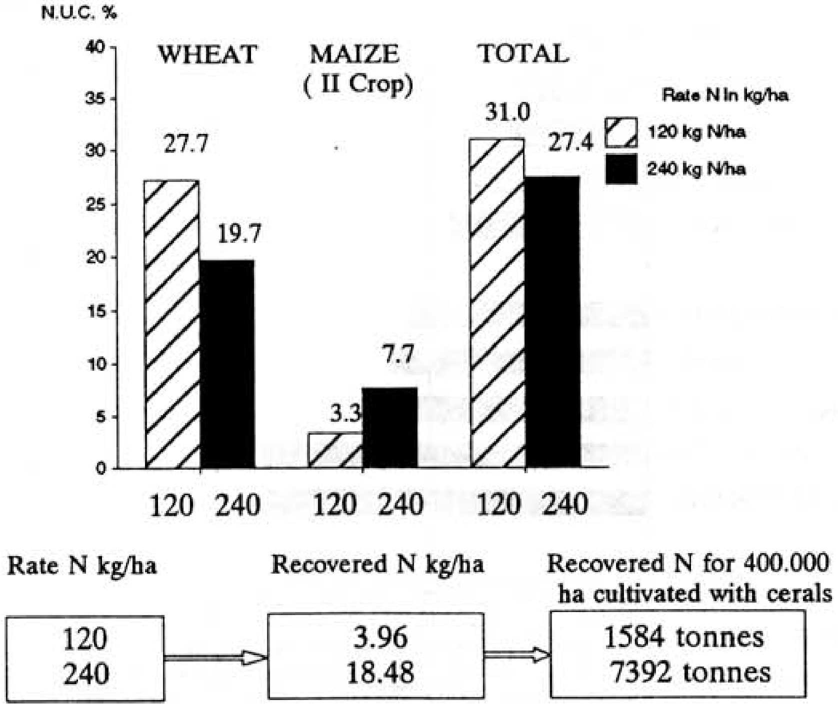
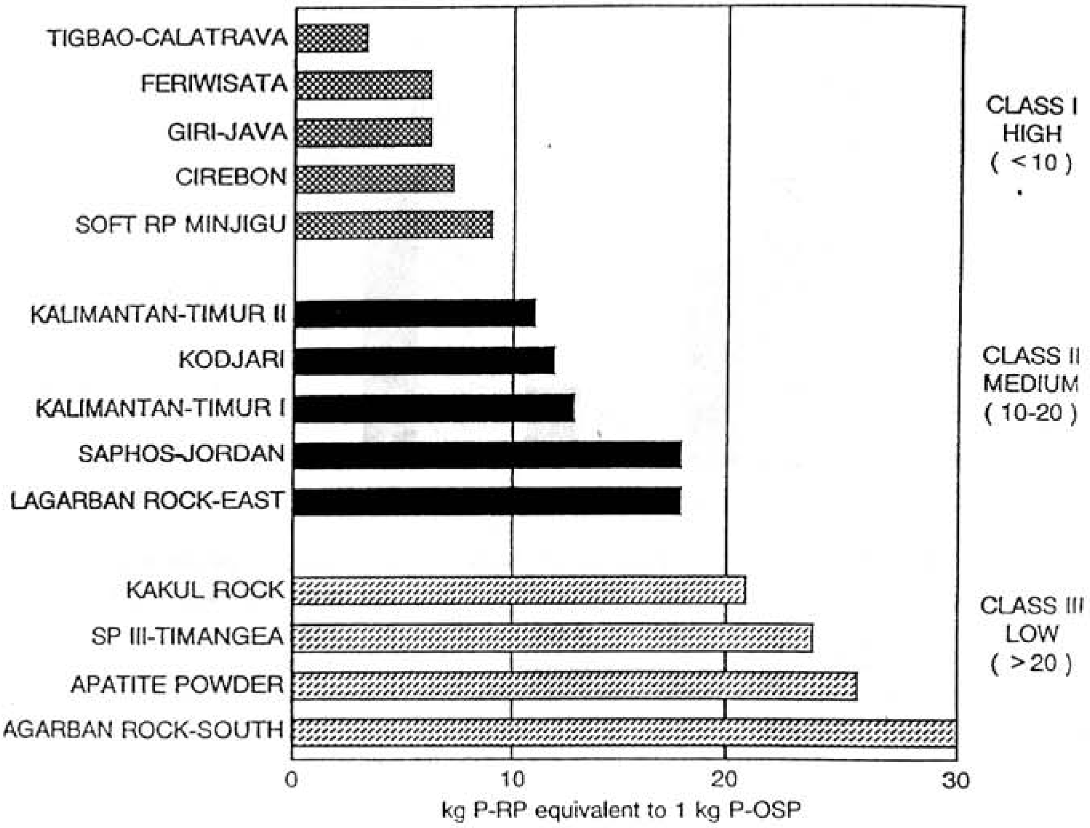


TABLE 14
Summary of results for agronomic evaluation of phosphate rock effectiveness

P fertilizer material	Grade %P	Full rate (R)			Half rate (R/2)		
		A_r values* mg P/pot	Amount kg equiv. to 1 kg P as OSP	1 kg OSP	A_r values* mg P/pot	Amount kg equiv. to 1 kg P as OSP	1 kg OSP
Gira-Java RP	10.00	262	7.6	6.6	167	6.0	5.2
Cirebon RP	13.38	146	13.7	8.9	154	6.5	4.2
Kalimantan-Timur I RP	10.75	113	17.7	14.3	79	12.7	10.3
Kalimantan-Timur II RP	9.88	108	18.5	16.3	94	10.6	9.3
Saphos-Jordan RP	11.13	101	19.8	15.5	56	17.9	14.0
SP III-Timangea RP	13.00	101	19.8	13.2	42	23.8	15.9
Feriwisata RP	5.13	na	-	-	165	6.1	10.3
Kakul RP	10.88	49	40.8	32.6	47	21.3	17.0
Lagarban RP-east	14.25	71	28.2	17.2	56	17.9	10.9
Lagarban RP-south	11.63	28	71.0	53.1	33	30.3	22.7
Apatite Powder	12.38	62	32.3	22.7	39	25.6	18.0
Soft RP Minjigu	10.63	139	14.4	11.8	109	9.2	7.5
Tigboa-Calatrava RP	10.25	744	2.7	2.3	320	3.1	2.6
Kodjari RP	10.25	139	14.4	12.2	83	12.1	13.3
SS** from Kakul RP	8.38	1635	1.2	1.2	826	1.2	1.2

* = expressed in mg P/pot as ordinary superphosphate (OSP) equivalent units
SS** = Single Super

FIGURE 12
Use of radiotracers (P-32 or P-33) for the agronomic evaluation of rock phosphate materials



response of maize to NCRP was similar to the yield response of triple superphosphate, but the response was higher in the second cropping.

Most of the research conducted with NCRP took place in tropical regions characterized by acid, low fertility, highly weathered soils. These soils generally exhibit pH less than 5,5 and low concentrations of P and Ca in the soil solution. The results obtained demonstrate that NCRP consistently increases crop yield not only with pasture and tree crops, but also with annual crops. Being a highly reactive rock, it dissolves faster than a low reactivity rock, providing P to the crop at the stage of growth, when it is needed. The residual effect is significant (Zaharah and Sharifuddin, 1990; Zaharah *et al.*, 1989).

CONCLUSION

Fertilizers labelled with the appropriate radio or stable isotope of interest represent an invaluable tool to select fertilization practices for different ecological conditions, to obtain quantitative information on the efficiency of the use by crops of nutrients from fertilizers, to study its movement in the soil and to avoid environmental pollution.

The use of isotope techniques proved to be a very valuable tool in the agronomic evaluation of fertilizer use efficiency. Quantitative and qualitative answers to such important questions on the effects that the fertilizer, its placement in the soil, its time of application and environmental and cultural practices have on the uptake of fertilizer nutrients by plants or its loss through movement in groundwater, and residual effects, can be obtained simply by using isotope labelling techniques.

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Bio-availability, cycling and balances of nutrients in the soil-plant system

Plant growth in a soil-plant atmosphere system involves 17 essential elements (nutrients) which plants absorb from their surroundings. Plant growth will be restricted by shortage of any one of these plant nutrients.

It has been known for centuries that soils differ widely in their fertility. Understanding the nature of both fertility and of plant nutrition, plant growth and crop production have therefore been of interest for a very long time. Only recently did it become evident that soil fertility depends on physical, chemical and biological properties of the soil and their interactions. Nevertheless, the present understanding of the dynamics of plant nutrients in agro-ecosystems, particularly in developing countries, is still incomplete; the ability quantitatively to predict the relationships between climatic factors, soil fertility, nutrient uptake, plant growth and crop production is lacking. This weakens our competence to evaluate sustainability of land use systems at e.g. local level, and to set up reasonable strategies for sustainable land use - aiming at increasing stability and productivity without irreversible land and/or ecological degradation. The fact that the bio-availability of plant nutrients and water are often the main factors limiting crop, food and livestock production, emphasizes the importance of optimal management at the field level of the bio-availability of nutrients and water.

This paper outlines some rate limiting and rate determining processes important both for plant nutrition and for the level of nutrient required for cycling in the soil-plant system.

SOIL-PLANT-ATMOSPHERE SYSTEM

An outline of the processes of nutrient transfer from soil into plants, circulation and recirculation of nutrients can be seen in Figure 1. An available nutrient is one that is present (a) in a form that can be absorbed by the plant, and (b) in a pool of nutrients having an effective diffusion coefficient (D_e) larger than 10^{-12} cm^2s^{-1}.

Supplying plants with inorganic nutrients, including trace elements, is one of the major functions of roots. Research in recent decades has shown that roots and soil interact via the

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PAPER 4.5

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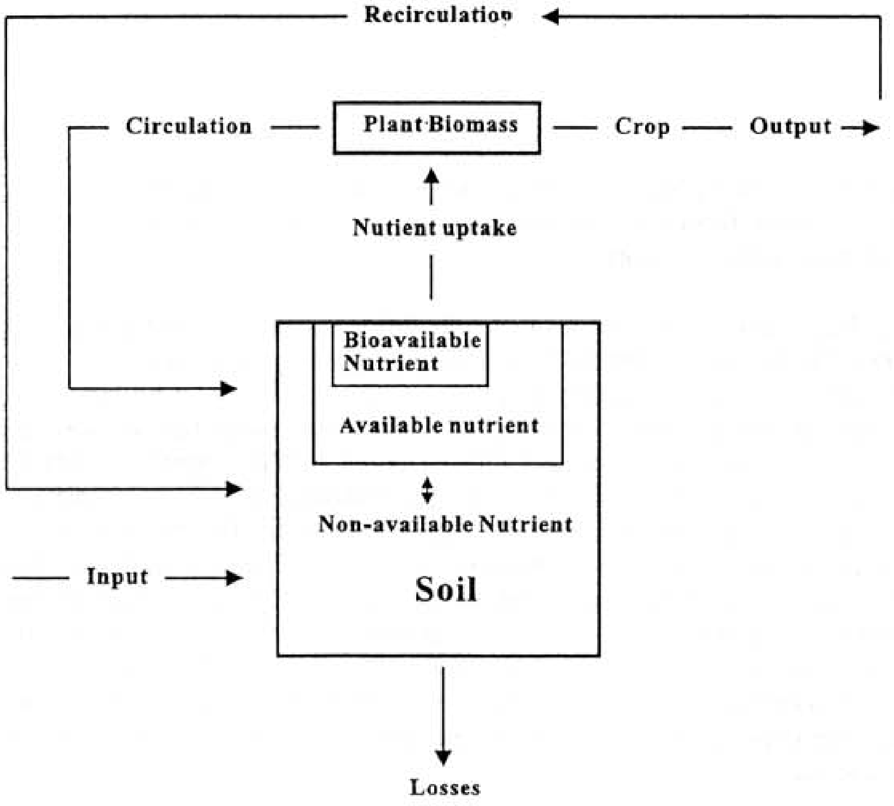
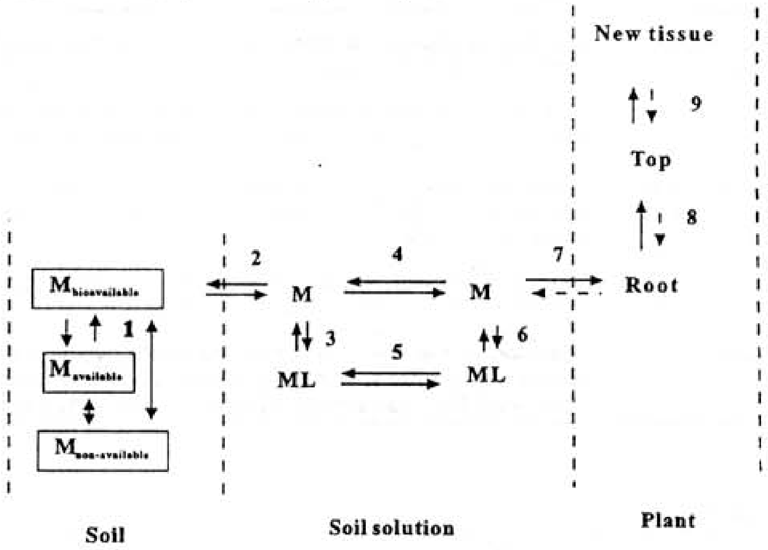
FIGURE 1
Flows of plant nutrients at field level



transfer of solutes from the soil into plants (Nye and Tinker, 1977; Barber, 1984; Nielsen, 1983; Jungk and Claassen, 1989; Gahoonia and Nielsen, 1991, 1992a, 1992b). Plant roots absorb their nutrients from the soil solution only in the dissolved state. Thus, the nutrients in the soil solution are the immediate nutrient source. The uptake of any nutrient, M, from soil by plants can be divided into a sequence of processes, as illustrated in Figure 2 (Nielsen, 1976). The $\longleftrightarrow$ denotes solid phase processes slowly approaching equilibrium and constitute the source/sink processes (U in Eq. 11) by which diffusible nutrients are being produced or removed by chemical, physical and biological transformation processes. In Figure 2, ML denotes complexes and ion pairs dissolved in the soil solution, and $\rightleftarrows$ denotes reversible processes which spontaneously and fast approach equilibrium. Depending on ion species, ion concentration at the root surface and on plant age, the symbol $\rightleftarrows$ denotes processes which may be irreversible. The irreversible processes are rate limiting and/or rate determining, although reversible processes may be rate limiting. Hence the rate determining processes (Figure 2) are the nutrient uptake into the roots, translocation/ circulation of the nutrient in the plant and/or the rate by which the nutrient is built into new tissue.

FIGURE 2
Solute movement in the soil plant atmosphere system



Usually only a small fraction of the plant available nutrients is dissolved in the soil solution. The bio-availability of nutrients to plant roots is for that reason governed by a large number of soil properties including, for example, the equilibrium of process number 2 in Figure 2. Here, a bio-available nutrient is one that is present in a pool of available nutrients and close enough to arrive at a nutrient and water absorbing root surfaces during the period of e.g. 10 days. The term 'bio-available amount of a nutrient in soil' includes then at least four different aspects: (1) the capability of solid phases to replenish the nutrient in the soil solution, (2) solute movement from the solid phases to the roots, (3) the synchronization and synlocation of available pools of nutrients and roots in the root zone, and (4) rhizosphere processes. The major processes and factors that contribute and interact in the movement of a nutrient from soil to plants are summarized in Table 1.

Nutrients bound to the solid soil phase are virtually immobile. As nutrients must reach the root surface and as roots must be able to absorb the nutrient from solution of very low concentration, rhizosphere processes and uptake kinetics are of fundamental importance for nutrient uptake by plants. The nutrient uptake by the root is usually a rate determining process under the conditions of nutrient shortage, although solute movement to the root may be rate limiting. The following sections intend to outline some of the processes involved in the transfer of nutrients in the rhizosphere and the kinetics of their uptake by the root.

Nutrient supply from soil to plant roots

Contact between the root surface and nutrients dissolved in the soil solution is a prerequisite for nutrient uptake. Contact can be brought about in two ways, e.g. by growth of roots to the sites where nutrients are located (root interception), and by movement of the nutrient from the bulk of the soil to the root surface.

TABLE 1

Processes and factors involved in nutrient transfer from soil to plant roots (see list of main symbols)

Process	Factors
Dissolution of the nutrient in the soil solution	Chemical and physical properties of the solid phases and activity of the microbial biomass
Root development	Root length, distribution of roots in the root zone, root morphology, root hairs, rate of root growth and root surface area
Solute movement by mass flow and diffusion to roots	Transpiration rate (w_o), concentration of the nutrient in the soil solution (c_b), effective diffusion coefficient (D_e), nutrient buffer power of the soil (b)
Nutrient uptake	Concentration of the nutrient at the root surface (c_o). Kinetics of nutrient uptake by the roots (I_{max}, Km and c_{min})
Rhizosphere effects	Depletion of the soil solution for nutrients by the roots. Root exudates as protons, reducing agents, chelates, organic anions, enzymes. Microbial activity. Mycorrhizal and Rhizobium symbioses

LIST OF MAIN SYMBOLS

Symbol	Definition	Units
α	root absorbing power	cm s^{-1}
b	solute buffer power (dC/dc)	
C	concentration of diffusible solute in soil	mol cm^{-3} of soil
c	concentration of solute in soil solution	mol cm^{-3} of liquid
c_b	concentration of solute in bulk soil solution	mol cm^{-3}
c_{min}	concentration of solute at which	mol cm^{-3}
c_o	concentration of soluble in soil solution at the root surface	mol cm^{-3}
c_i	initial concentration of solute in soil solution	mol cm^{-3}
D_e	diffusion coefficient of solute in soil	cm^2s^{-1}
D_o	diffusion coefficient of solute in the soil solution	cm^2s^{-1}
F_T	total net flux of solute	mol $cm^{-2}s^{-1}$
F_m	net flux of solute by mass flow	mol $cm^{-2}s^{-1}$
	mean net influx at the root surface	mol $cm^{-2}s^{-1}$
F_d	net flux of solute by diffusion	mol $cm^{-2}s^{-1}$
θ	soil moisture fraction by volume	cm^3cm^{-3}
f	diffusion impedance factor	
t	time	s
$\overline{In}$	mean net influx into roots per unit length	mol $s^{-1}cm^{-1}$
$\overline{I}_{max}$	mean maximal net influx into roots per unit length	mol $s^{-1}cm^{-1}$
Km	Michaelis-Menten factor $\overline{In} = ½ \overline{I}_{max}$ if $c_0 = Km + c_{min}$	mol cm^{-3}
L^*	root length per g of plant biomass	cm g^{-1}
	source/sink term. The rate at which diffusible nutrient is being produced or removed by chemical, physical or biological transformation processes	mol $cm^{-3}s^{-1}$
	water flux	$cm^3cm^{-2}s^{-1}$
w_o	water flux at the root surface	$cm^3cm^{-2}s^{-1}$
	radial distance from the centre of the root	cm
r_o	root radius	cm

Root interception is the process by which a nutrient in the soil solution is intercepted by the growth of the root through the soil, without the necessity of moving to the root surface (Barber *et al.*, 1963). As the root volume of annual crop plants in the densely rooted plough layer is usually smaller than 1% of the soil volume, less than 1% of the available nutrient in the soil can reach the root interception. If it is assumed that root hairs effectively 'touch' the soil 0.5 mm out from the root surface the volume of interception would increase to about 5% of the total soil volume.

However, nutrients have to move over a certain distance in the soil solution and cell wall, before they reach the outside cell membrane of a root cortical cell for uptake. The mechanisms of transport are mass flow and diffusion (Barber *et al.*, 1963; Nye and Tinker, 1977). The driving force for the net movement of nutrients is the water and the selective nutrient uptake by the plant root. When roots take up nutrients and water at their surface, they create gradients in the soil water potential and in the chemical potential (concentration) of the nutrient in the ambient soil solution. The results are net movements of water and nutrients along these gradients by simultaneous mass flow and diffusion. The total flux (F_T) is the sum of both:

$$F_T = F_m + F_d \tag{1}$$

where F_m is mass flow and F_d is diffusive flux.

Mass flow is the movement of nutrients through the soil to the root with the flow of water caused by the uptake of water by the plant root. The amount of nutrient transferred by mass flow is related to the water used and the concentration of nutrients in the soil solution at the root surface.

$$F_m = w_o c_o \tag{2}$$

where w_0 is the water flux into root ($cm^3 cm^{-2} s^{-1}$) at the root surface and c_0 is the nutrient concentration of soil solution at the root surface (mole cm^{-3}). The expected rates of water flux at the root surface are 0.2 to 1 10^{-6} cm s^{-1} (Barber, 1984).

Diffusion is the spontaneous movement of nutrient or molecules which is caused by thermal agitation. Concentration gradients are necessary for net movement of a solute by diffusion. If mass flow accounts for smaller or higher quantities of ions than those actually taken up by the roots, the resulting concentration gradient would cause net diffusion through the soil root interface.

The flux, F_d, by diffusion can be expressed by

$$F_d = -D_e b \frac{dc}{dr} \tag{3}$$

The $b = dC/dc$ in Eq. 3 denotes the soil buffer power for the nutrient concerned, where c is the concentration of the nutrient in the soil solution, and C is the total concentration of diffusible nutrient in the soil. The latter is the sum of the amount of nutrient in the soil solution and the amount of adsorbed nutrient which is able to replenish the nutrient in the soil solution spontaneously.

D_e denotes the effective diffusion coefficient in a homogeneous soil. D_e differs between media, but it can be calculated in relation to the diffusion coefficient D_0 for the nutrient in free soil solution. The influence of soil on diffusion can be expressed by the following equation (Nye, 1966):

$$D_e = D_0 \theta f / b \tag{4}$$

where θ is the volumetric water content expressed as a fraction, and f is the impedance factor that essentially allows for the increase in actual diffusion distance because of the tortuous pathway of water filled soil pores and water films. The volumetric water content which allows a reasonable root activity is between 0.1 and 0.4. The value of (f) increases with increase in water content (Rowell *et al.*, 1967) whereas the buffer power remains constant with change in soil moisture at the same bulk density (Bhadoria *et al.*, 1991). It may be seen from a study of Barraclough and Tinker (1981) that the relation between f and θ can be expressed empirically by $f = 1.58\ \theta - 0.17$ for $\theta >$ about 0.11. From this it may be estimated that D_e decreases about 18 times if θ decrease from 0.40 to 0.15.

The average distance of diffusion, $\Delta\bar{x}$, can be expressed by equation 5 (Jost, 1952)

$$\Delta\bar{x} = \sqrt{2 D_e t} \tag{5}$$

Using Eq. 5 it may be calculated that a non-available nutrient ($D_e = 10^{-12}$ cm^2 s^{-1}) is one which only moves $\sqrt{(2 \bullet 10^{-12} \bullet 8.64 \bullet 10^4 \bullet 10)} = 0.013$ cm in 10 days on the average. For example, using Eq.5 and data in Table 2, phosphorus would be expected to move $\sqrt{(2 \bullet 10^{-9} \bullet 8.64 \bullet 10^4 \bullet 10)} = 0.04$ cm in 10 days on the average. The corresponding value for calcium and magnesium would be 0.13 cm, for potassium it would be 0.4 cm and for nitrate 1.3 cm. Such information is important for understanding bio-availability and uptake of nutrients by plants growing in soil, because it indicates that the nutrient mobility in the soil is so low for phosphorus and micro nutrients that only soil close to the roots supplies nutrients to the plants. Under these conditions rhizosphere processes are of special importance.

TABLE 2

Expected effective diffusion coefficients of some nutrients in soil at field capacity of water content (from Barber, 1984)

Element	D_e (cm^{2}s^{-1})
Nitrate	$1 \cdot 10^{-6}$
Potassium	$1 \cdot 10^{-7}$
Boron	$1 \cdot 10^{-7}$
Magnesium	$1 \cdot 10^{-8}$
Calcium	$1 \cdot 10^{-8}$
Phosphorus	$1 \cdot 10^{-9}$
Manganese	$1 \cdot 10^{-9}$
Molybdenum	$1 \cdot 10^{-9}$
Zinc	$1 \cdot 10^{-9}$
Iron	$1 \cdot 10^{10}$

If the density of roots (radius = 0.01 cm) in the top soil is 5 cm per cm^3 of soil and available phosphorus is withdrawn effectively 0.04 cm out from the root surface as calculated above, it can be estimated that the volume of bio-available phosphorus is $5\pi(0.05)^2 = 0.04$ cm^3 per cm^3 of soil. This indicates that the quantity of bio-available phosphorus corresponds to 4% of the available phosphorus pool. If root hairs withdraw phosphorus effectively 0.5 mm from the root surface it can be estimated that the volume of bio-available phosphorus is $5\pi(0.1)^2 = 0.16$ cm^3 per cm^3 of soil. This indicates that the quantity of bio-available phosphorus now corresponds to 16% of the available phosphorus pool. However, this may easily be reduced to one tenth if the soil moisture decreases to e.g. $\theta = 0.15$.

If similarly potassium is withdrawn effectively 0.4 cm out from the root surface and nitrate is withdrawn 1.3 cm out from the root surface it can be estimated that a root density of only 2 to 3 cm^{-2} is necessary to obtain all the available soil potassium bio-available. The root density necessary to obtain all the available nitrate is then only 0.2 cm^{-2}. Hence at a root density of 5 cm^{-2} and soil at field capacity of water all the available potassium and nitrate are bio-available.

Rhizosphere processes

The ability of the root system to absorb nutrients depends on:

- net influx per unit of root length ($\overline{In}$);
- root length, root area and root length per unit of plant biomass (L*);
- duration of activity of each root segment, e.g. 10 days.

Furthermore, the contact area between root and soil solution is increased by the development of root hairs and by mycorrhizial symbiosis.

Mean net influx of nutrient into plants per unit of plant biomass weight under conditions in which the rate determining step is located in the root can be expressed by (Nielsen, 1976)

$$\overline{In}L^{*} = \frac{L^{*}\bar{I}_{\max}(c_0 - c_{min}}{Km + c_0 - c_{min}} \tag{6}$$

Mean net influx of nutrient into plants per unit of root length can then be expressed by

$$\overline{In} = \frac{\bar{I}_{\max}\,(c_0 - c_{\min})}{Km + c_0 - c_{\min}} \tag{7}$$

$\bar{I}_{\max}$(mole $cm^{-1}s^{-1}$) is the mean maximal net influx, Km (mole cm^{-3}) is the Michaelis-Menten factor, c_0 is the concentration of the nutrient at the root surface, and c_{min} is the nutrient concentration at which $\overline{In} = 0$. Further, $\overline{In} = ½\,\bar{I}_{\max}$, if $c_0 = Km + c_{min}$. The values of the parameters $\bar{I}_{\max}$, Km and c_{min} vary according to the plant nutrient, temperature, plant species/genotype and plant age. Furthermore, kinetics of nutrient uptake by roots may be influenced by ion interactions. Determined values of L*, $\bar{I}_{\max}$, Km and c_{min} for uptake of several nutrients by several plant species or genotypes, and obtained under conditions in which the rate determining step of nutrient uptake was located in the roots are shown in Tables 3, 4 and 5. The data show that the values of L*, $\bar{I}_{\max}$, Km and c_{min} vary considerably between nutrient and between plant species and genotypes and thereby the efficiency by which these plants utilize soil as a source of nutrients.

TABLE 3
Root length (L*) per unit weight of plant biomass, root radius (r_0), mean maximal net influx of P per cm roots ($\bar{I}_{max}$), Michaelis-Menten factor (Km), concentration (c_{min}) of P at which $\bar{In} = 0$ and mean maximal net influx of P per cm^2 of root surface ($\bar{F}_{max}$) for uptake of phosphorus (P) by several plant species (Nielsen, 1983)

Plant species	L*, m root g^{-1} of DM 25^a	 35^a	r_0 cm	$\bar{I}_{max}$ pmole P cm^{-1} s^{-1}	Km μM P	c_{min} μM P	$\bar{F}_{max}$ pmole P cm^{-2} s^{-1}
Buckwheat	159	65	0.009	0.10	3.5	0.017	1.77
Pea	74	46	0.017	0.12	2.6	0.028	1.12
Rape	93	59	0.012	0.12	4.7	0.011	1.59
Lupin	11	15	0.025	0.41	4.5	0.082	2.61
Sugar beet	85	71	0.011	0.11	2.7	0.018	1.59

[a] Days after germination.

TABLE 4
Root length (L*) per unit weight of plant biomass, root radius (r_0), mean maximal net influx of P per cm roots ($\bar{I}_{max}$), Michaelis-Menten factor (Km), concentration (c_{min}) of P at which $\bar{In} = 0$ and mean maximal net influx of P per cm^2 of root surface ($\bar{F}_{max}$) for uptake of phosphorus (P) by several genotypes of barley and maize (Nielsen, 1983)

Plant species	L*, m root g^{-1} of DM 25^a	r_0 cm	$\bar{I}_{max}$ pmole P cm^{-1} s^{-1}	Km μM P	c_{min} μM P	$\bar{F}_{max}$ pmole P cm^{-2} s^{-1}
Barley genotypes						
Salka	65	0.012	0.08	2.9	0.02	1.06
Lofa	77	0.011	0.08	4.1	0.04	1.16
Rupal	46	0.012	0.10	3.6	0.04	1.33
Nürenberg	68	0.010	0.11	3.6	0.06	1.75
Mona	42	0.012	0.14	5.5	0.05	1.88
Zita	57	0.012	0.12	4.7	0.03	1.59
Maize genotypes						
C103 x W64A	26	0.014	0.13	0.6	0.06	1.48
H60 x W64A	28	0.014	0.15	1.3	0.06	1.71
H60 x C103	22	0.015	0.23	1.5	0.04	2.44
H84 x H99	29	0.013	0.34	2.4	0.04	4.16
Pioneer 3369A	30	0.014	0.26	2.0	0.06	2.96

[a] Days after germination.

A systematic attempt to estimate values of $\bar{I}_{max}$, Km and c_{min} for various micronutrients has not been attempted so far. However, Carroll and Loneregan (1969) studied zinc uptake by plant roots at a concentration as low as 0.01 μM Zn in solution. A study of kinetics of copper uptake by barley (Nielsen, 1976) showed, that Km = 0.11 μmol (Cu^{2+} + CuL) and c_{min} = 0.045 μmol (Cu^{2+} + CuL). As about 1 % only of the total Cu (= Cu^{2+} + CuL) is free Cu-ions, the above values of Km and c_{min} correspond to 0.001 and 0.0005 μM Cu^{2+}, respectively.

TABLE 5

Mean maximal net influx into roots $\bar{I}_{max}$, Michaelis-Menten factor (Km) and concentration (c_{min} of P at which $\overline{In}$ = 0 for uptake of several nutrients by maize and wheat (from Barber, 1984)

Plant species	Plant age (days)	Nutrient	$\bar{I}_{max}$ pmole P cm^{-1} s^{-1}	Km (μM P)	c_{min} (μM P)
Maize	18-22	NO_3-N	1.0	10	4
Maize	14-22	P	0.4	3	0.2
Maize	18	K	4.0	16	1
Wheat	20-38	P	0.14	6	-
Wheat	20-40	K	0.7	7	-
Wheat	30-40	Ca	0.16	5	-
Wheat	20-40	Mg	0.04	1	-

The relation between mean total net flux (Eq. 1) to 1 cm^2 of the root surface and mean net influx ($\overline{In}/2\pi r_0 = \alpha c_0$) can be expressed by:

$$F_T = F_d + F_m \approx \overline{In} \,/\, 2\pi r_o = \overline{F}n = \alpha c_o \tag{8}$$

where α is the root absorbing power as developed by Nye and Tinker (1977). From Eq. 8 it may be seen that the concentration of a nutrient at the root surface is determined by the ratios F_T/α and as $c_0 \approx \overline{F}n/\alpha \approx F_T/\alpha$. The integrated effect of $\bar{I}_{max}$, Km, c_{min}, L* and r_0 can then be expressed by the root absorbing power (Nielsen, 1979), as follows:

$$\alpha = \frac{\bar{I}_{max}(c_0 - c_{min})}{2\pi r_0 c_0 (Km + c_0 - c_{min})} \tag{9}$$

$$\alpha L^* = \frac{L^* \bar{I}_{max} \, (c_0 - c_{min})}{2\pi r_0 c_0 \, (Km + c_0 - c_{min})} \tag{10}$$

How the root absorbing power (α) for P varies with its concentration (c_0) at the root surface is of special interest for plant growth in soils low in plant available P. Based on data in Table 3 and by use of Eq. 9, Figure 3 shows the variation of α with increasing c_0. Particularly rape but also sugar beet and buckwheat have a higher root absorbing power than pea and lupine at c_0 lower than 0.05 μM P. Further at c_0 between e.g. 0.1 and 0.3 μM P α for sugar beet and buckwheat are considerably higher than α for rape, pea and lupine.

In an evaluation of both the capability to use soil as a source of P and the possibility for P nutrition, the variation of αL* with c_0 is more valuable. Based on data in Tables 3 and 4 and in Eq. 10, Figures 4, 5, and 6 show how α* vary with increasing c_0 of P. The figures show as expected that αL* varied more between plant species than within genotypes of the same plant species (maize and spring barley). The cause for this was partially a larger

FIGURE 3
Root absorbing power (*α*) of phosphorus (P) by crop plants at varying P concentration at the root surface

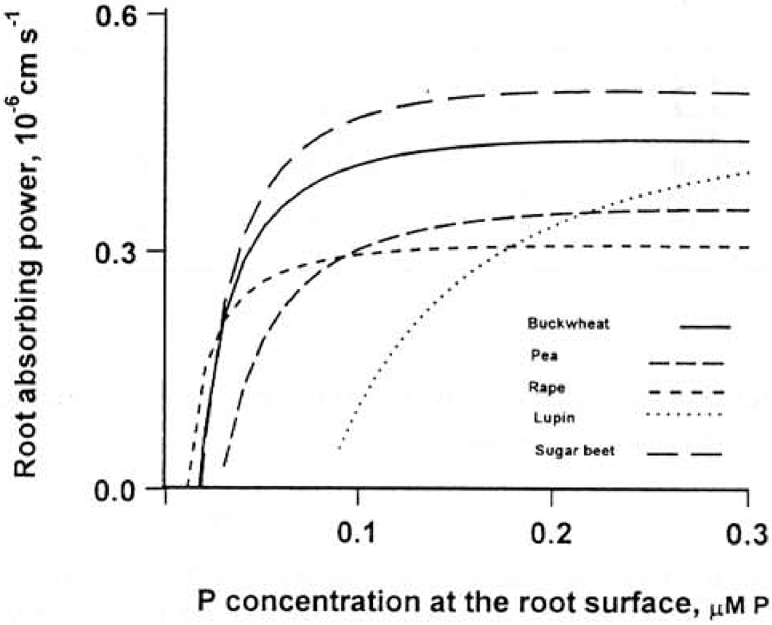


FIGURE 4
Root absorbing power (*α*L*) of phosphorus (P) per g of plant biomass by crop plants at varying P concentration at the root surface

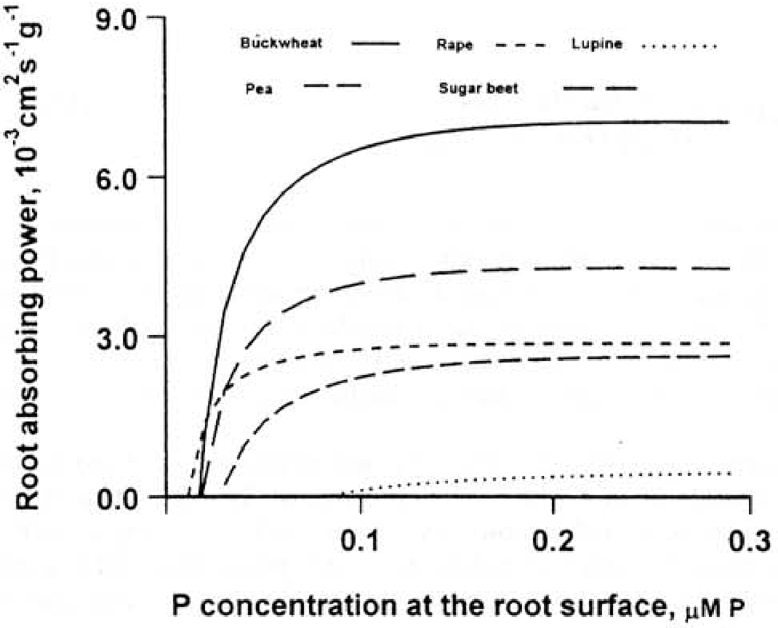


FIGURE 5

Root absorbing power (αL^*) of phosphorus (P) per g of plant biomass by maize genotypes at varying P concentration at the root surface

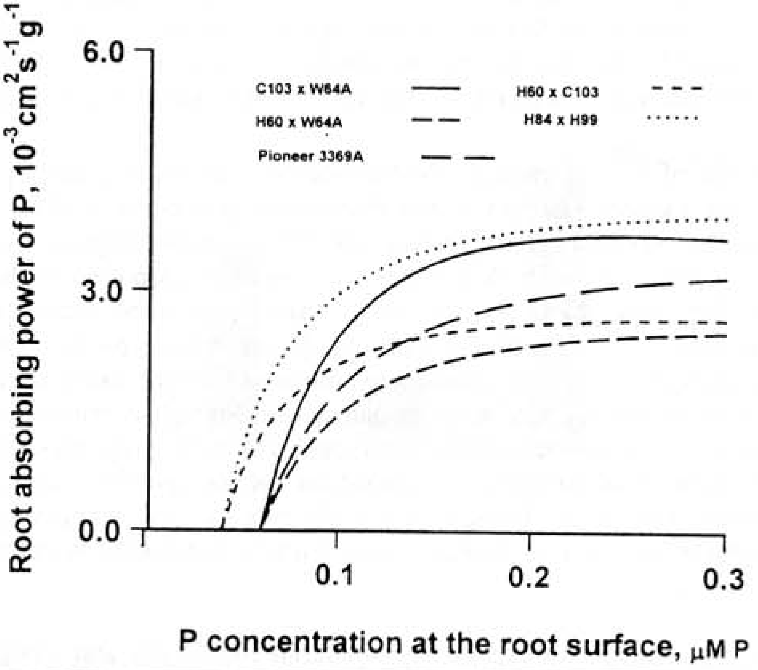
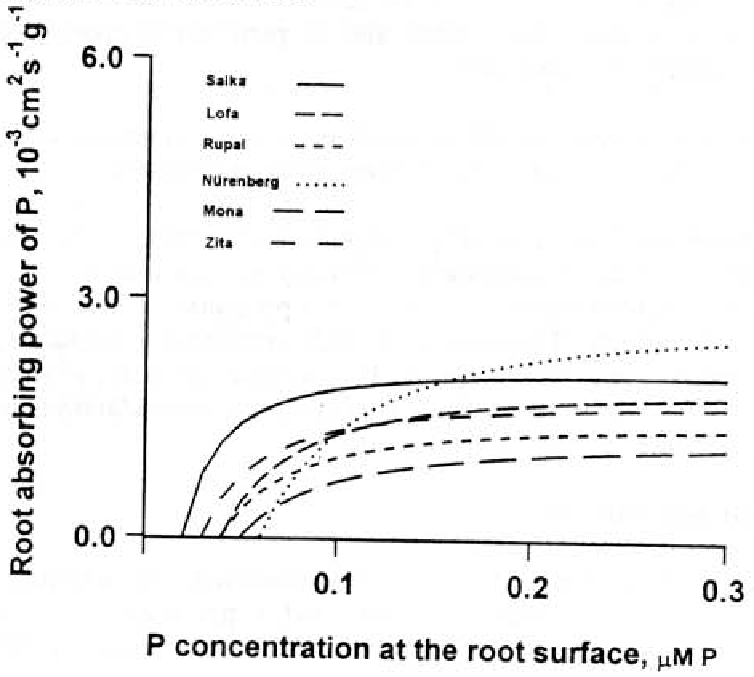


FIGURE 6

Root absorbing power (αL^*) of phosphorus (P) per g of plant biomass by barley genotypes at varying P concentration at the root surface



variation in L* between plant species than between the studied genotypes of maize and barley (Table 4). Even so it can be concluded from Figure 5 that H84 x H99 and H60 x C103 are better in P uptake at low soil P than C103 x W64A, H60 x W64A and Pioneer, and that Salka (Figure 6) is better in P uptake than the other 5 barley genotypes at low soil P. In conclusion it can be emphasized that the latitude of variations in αL^* is considerable. This indicates that it should be possible to improve the efficiency of P uptake from soils low in P by selecting genotypes with a high αL^*-value at low soil P during the main growth period.

The actual value of c_0 is affected by the balance between $\overline{In}/2\pi r_0$ and $F_T = F_d + F_m$, and affected by root induced changes in the rhizosphere as emphasized by, for example, Marschner (1986).The conditions in the rhizosphere differ in many respects from those in the bulk soil. Roots not only act as a sink for ions and nutrient transported to the root surface by mass flow and diffusion. Roots also selectively take up ions and water which may lead to depletion or accumulation of ions and nutrient. Roots release protons and CO_2 which change pH of the rhizosphere. Roots consume or release O_2 which cause alternations in the redox potential. Root exudation may mobilize nutrients, although it primarily is a substrate for the micro-organisms in the rhizosphere. Although chemical properties of the bulk soil (e.g. the pH and the level of nutrients) are important for root growth and mineral nutrient availability, the conditions in the rhizosphere and the root induced changes are decisive for mineral nutrient uptake, e.g. via an increase of the nutrient concentration in the soil solution (M and ML, Figure 2).

Most of the root exudates are gelatinous material (mucilage) and sloughed-off cells, particularly root cap cells. Free soluble exudates (low-molecular-weight organic compounds) are only a minor part of the rhizo-deposition. The main constituents of free root exudates are sugars, organic acids, amino acids, and phenolic compounds. Quantitatively, sugars and organic acids are the major compounds. Organic acids and phenolic compounds are soluble chelators which may enhance the rate of mobilization of nutrient in the rhizosphere. Furthermore, some of the organic acids and in particular phenolic compounds act as reductants, for example $Fe^{3+}$and Mn^{4+}.

A particular sort of exudates (phytosiderophores) exists in grasses including grain crops for the solubilization of Fe^{3+} and other nutrient in the rhizosphere.

In the rhizosphere there is usually a depletion of nutrients. This leads to increased solubility of soil organic matter, and thereby mobility of many complexing nutrients. On the other hand, a higher rate of water uptake than of a particular ion may lead to accumulation of that ion in the rhizosphere. This has been directly measured for sulphate in the rhizosphere of onion root (see Nye and Tinker, 1977). Precipitation of $CaSO_4$ in rhizosphere soil has been demonstrated too (see Barber, 1984). However, salt accumulation in the rhizosphere is of particular importance in saline soils.

Rhizosphere pH and redox potential

Redox reactions in the soil plant system are highly correlated to the activities of protons (a_{H+}) and electrons (a_{e-}) and usually linearly related to pH + pe, where pe = - log a_e. At 25 °C is pe $\cong \Delta E/59.2$ in which ΔE denotes the measured redox potential in millivolt.

Changes in rhizosphere pH are brought about predominantly by variations of the net flux of protons from the root. This net flux of protons is related to the cation/anion uptake ratio and is a consequence of the need to maintain electrochemical balance both in root cells and in the soil solution. The N-forms (NH_4-N or NO_3-N) absorbed by the root have the highest influence on the cation/anion uptake ratio and hence on rhizosphere pH. NO_3-N uptake is correlated with lower net efflux of protons than NH_4-N uptake.

The pH differences between the rhizosphere and the bulk soil may be as high as 1 to 2 pH units (Gahoonia and Nielsen, 1992b). Considerable differences in the rhizosphere pH exist among plant species growing in the same soil. Buckwheat and chickpea have a lower rhizosphere pH than that of wheat and maize (Raij and Diest, 1979; Marschner and Römheld, 1983).

Plants with N_2 fixation from the atmosphere rather than NH_4-N and NO_3-N uptakes absorb many more cations than anions since uncharged N_2 enters the root nodules resulting in proton excess equal to that of urea nutrition but a lower proton excess than that of NH_4-N nutrition. In alfalfa, N_2 fixation would produce soil acidity equivalent to about 600 kg $CaCO_3ha^{-1}$, if 10 tons ha^{-1} of top dry matter are produced.

For well-aerated arable soils reliable data on redox potentials in the rhizosphere are lacking. It is emphasized that it is difficult to make precise measurements even in the bulk soil. However, even well-aerated arable soils contain anaerobic microsites varying in location and size. Such micro sites seem to be more abundant in the rhizosphere due to O_2consumption by both microbial and root respiration. In submerged soils rice plants, for example, maintain high redox potentials in the rhizosphere by translocation of O_2 from the shoots to the roots.

Main elements in modelling of nutrient dynamics at the soil root interface

The general equation of continuity used to describe movements in a direction normal to a cylinder, e.g. to a root, may be expressed as

$$\left[b\frac{\partial c}{\partial t}\right]_r = -\left[\frac{1}{r}\ \frac{\partial rF_T}{\partial r}\right]_t + U_{r,t} \qquad \textbf{(11)}$$

Solution of Eq. 7 depends on knowledge of the value of the source/sink term, U, at various r and t values.

Considering the simplified case in which U = 0, Eq. 7 may be reduced to

$$\left[b\frac{\partial c}{\partial t}\right]_r = -\left[\frac{1}{r}\ \frac{\partial rF_T}{\partial r}\right]_t = \frac{1}{r}\frac{\partial}{\partial r}\left[rD_e b\frac{dc}{dr} + rwc\right]_{r,t} \qquad \textbf{(12)}$$

The integration of Eq. 8 may then be performed under various initial and boundary conditions, e.g.

if $t = 0$, $r > r_0$ then $c = c_i = c_b$
if $t > 0$ $r = r_0$ then

the boundary condition at the root surface is

$$2\pi r_0\left[D_e b\frac{dc}{dr} + w_0 c_0\right] = \frac{\bar{I}_{\max}(c_0 - c_{\min}]}{Km + c_0 - c_{\min}} \tag{13}$$

and, when $t > 0$, $r = r_1$ (half distance between roots) then

the boundary condition at the half distance between parallel roots is

$$D_e b\frac{dc}{dr} + \frac{r_0}{r_1}w_0 c_0 = 0$$

in which $r_1 = \frac{1}{\sqrt{\pi L_v}}$ where L_v denotes root density (cm/cm^{-3}).

As the depletion zone spreads outward with time until it coincides with the boundary of the equivalent cylinder at:

$$r_1 = \frac{1}{\sqrt{\pi L_v}}$$

simulation of this is achieved by inserting the condition

$$(r_1)_t = 2\sqrt{D_e t} + r_0 \text{ until } 2\sqrt{D_e t} + r_0 \geq \frac{1}{\sqrt{\pi L_v}}$$

into the programme calculation as suggested by Nye and Tinker (1977).

In most cases, however, the source/sink term U (Eq. 11.) is of importance and thereby $U \neq 0$, particularly in the rhizosphere. The assumption above that $U = 0$ is therefore justified only for smaller periods of time.

Understanding in a quantitative way how U for various nutrients varies in the rhizosphere is a challenge, because, as outlined above, the rhizosphere processes govern the extent and the efficiency by which crop plants use soil and fertilizers as sources of nutrients and determine the level of nutrient cycling required to meet the nutrient demands of the crop plants.

The fact that nitrate nitrogen and sulphate have a D_e as high as 10^{-6} cm^{2}s^{-1} implies that the dynamics of organic matter turnover, net nitrogen mineralization and nitrification are their key processes in this case. Some success in the modelling of carbon and nitrogen in soils has been achieved by, for example, Hansen *et al.* (1990; 1991). This model simulates the dynamics of water, organic matter and nitrogen in the soil, the uptake of nitrogen and water by the considered crop plants, and crop production as affected by light, temperature, water and nitrogen uptakes.

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Methodologies for comparison of local and external plant nutrition sources

The use of local sources of nutrients is a subject of interest in most parts of the world, although often for quite different reasons. In some cases it is thought that local sources might be cheaper for the producers and in other cases the local sources must be used because of scarcity of hard currency to import fertilizers. But almost everywhere there is a need to dispose of a variety of residues produced by society and their use as fertilizers is one of the most important options.

Besides the conventional nutrient sources, represented by the chemical fertilizers, there exist a variety of alternatives of possible nutrient sources that can eventually be used as fertilizers. Such products may contain several nutrients, often with different degrees of availability, act as organic or chemical amendments or possess hazardous constituents. This combination of components makes the characterization of such products a difficult task. Furthermore, there is always the possibility of the development of new fertilizers, including a variety of combinations of products and processes that often affect the availability of the nutrients.

In this paper the methods used to evaluate fertilizer materials are discussed, with emphasis on the evaluation of local as compared to external sources.

LOCAL AND EXTERNAL SOURCES OF NUTRIENTS

It is not possible to draw a line between local and external sources, but in many conditions it might be fair to consider the commercial fertilizers as 'external sources' and all other alternatives as 'local sources', although some products can be classified in either of the two cases. Not much attention will be given to commercial fertilizers since they are well known, although the principles that will be discussed here apply to any type of fertilizer.

Normally the most important local sources of nutrients are of organic origin, representing residues of plant and animal life. Sometimes a distinction is made between products with a high organic matter content and rather low contents of mineral nutrients, called manure, and products with higher contents of nutrients, called organic fertilizers (Cooke, 1982). From the practical point of view this distinction is not so significant, mainly

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PAPER 4.6

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because of the recognition of the important role of organic matter for crop production and the need to dispose of organic materials on soils, even when their mineral content is low. Therefore all materials will here be named 'fertilizers'.

The most important organic fertilizers are animal manure, municipal composts and sewage sludge, but there exist a variety of local products, organic or inorganic, that can be applied to soils as fertilizers. A thorough description of organic fertilizers, including nutrient contents can be found, among others, in the book of Cooke (1982). The most important inorganic sources include ashes, basic slag, aluminum calcium phosphates and ground phosphate rock. Limestone and gypsum, although mainly used as amendments, are important sources of the nutrients calcium, magnesium and sulphur.

CHEMICAL CONTENT

The most obvious and important characterization of any type of fertilizer is the total content of nutrients. For several reasons, the chemical analysis of local sources, especially of organic residues, is seldom obtained. Usually these products are cheap and quite heterogeneous and therefore their use is directed by general recommendations that consider average contents of nutrients. Often this is adequate, especially if analyses are expensive and difficult to obtain.

If a better evaluation of the products is of interest, a chemical analysis is necessary. A very comprehensive and inexpensive analysis can be obtained by the adaptation of the routine procedures normally used for plant analysis. Care must be taken, however, to obtain representative samples, which is difficult for heterogeneous solid materials or fluid suspensions. On the other hand, there is no need for very low analytical errors in the case of these materials that are inherently heterogeneous and of low value. Water insoluble materials, such as phosphate rocks, require also a particle size analysis for an adequate characterization.

Organic fertilizers are usually characterized by their total carbon (or organic matter) and nitrogen contents and the resulting C/N ratio, which is indicative of nitrogen release. The analysis of other elements is often useful, especially of phosphorus and potassium. The analysis of calcium, magnesium and micronutrients can also be made, although the results, not being used for the calculation of nutrient budgets, have only an informative value. For some types of materials, such as sludge and municipal composts, the analysis of heavy metals, such as cadmium, nickel, chromium and lead is also advisable.

The total contents of the nutrients nitrogen, phosphorus and potassium applied as organic fertilizers should be considered in fertilization plans to reduce the use of chemical sources. Heavy metal contents must be taken into account for certain materials to avoid excessive build-up in soils.

The evaluation of phosphates has special requirements. Besides the total content, the solubility in some specific extractants under standardized conditions is of importance (Engelstad and Terman, 1980; Cooke, 1982). Among others, Léon *et al.* (1986) and Rajan *et al.* (1992) showed that phosphate rocks can be classified by their agronomic potential using rapid laboratory tests, extracting P with solutions of neutral ammonium citrate, 2% citric acid or 2% formic acid. Water solubility is important for the characterization of the most commonly used phosphates of calcium and ammonium (Engelstad and Terman, 1980).

In many cases a chemical analysis will suffice to characterize a fertilizer completely, if a correct use is made of the enormous amount of information already available. However, sometimes doubts might persist and experiments might be necessary to reach conclusions on the plant availability of nutrients in unknown sources.

MONITORING BY SOIL AND PLANT ANALYSIS

Soil analysis can be used to monitor the increase of plant available forms of nutrients or toxic elements in soils. Plant analysis can be used to evaluate the transfer to plants of nutrients added to soils as fertilizers.

Nitrogen in organic materials must be mineralized to be readily available in ammonium and nitrate forms. The mineralization is affected by many factors and generally occurs in an exponential decay curve that might extend over years. If organic fertilizer is added regularly, as happens with manure, yearly determinations of total carbon and nitrogen contents in soil can be used to evaluate the build-up as compared with a control treatment. Ammonium and nitrate can be determined to evaluate the mineralization of organic materials added to soil, but the dynamics and mobility of the mineral forms of nitrogen in soil requires a large number of samples at different depths and periods. Furthermore, organic N sources, such as manure, present a cumulative effect over the years of application (Xie and Mackenzie, 1986). Another alternative is measuring losses from soils by volatilization, as was done by Carter *et al.* (1986), determining ammonium losses from applied urea.

Phosphorus has a complex behaviour in soils, but reasonable comparisons can be made of the effects of different fertilizers added to soils, provided the P extractant presents good correlation with plant uptake and does not dissolve unaltered phosphate particles. One such extractant is the anion exchange resin, that does not extract less available forms of aluminum and calcium phosphates added to soil as fertilizers (Raij and Diest, 1980). Syers and MacKay (1986) showed that the Bray 1 extractant was adequate to represent plant available P in soil from an applied phosphate rock, but not from superphosphate. For most P extractants, recovery of the amounts added as fertilizer is low, but it is important that residues of phosphates that are not available to plants are not dissolved.

Potassium, calcium, magnesium and inorganic sulphur additions by fertilizers can be almost quantitatively recovered by soil analysis. For micronutrients, comparisons of different sources added to the soils can also be made by soil analysis but, except for boron, recovery is low due the strong interaction of the elements with the soil particles. The build-up of possibly toxic heavy metals contents in soils can also be monitored by soil analysis whereby DTPA or other extractants, used for micronutrients, are adequate (Risser and Baker, 1990).

Plant analysis is especially useful in pot experiments to determine total uptake by plants of given elements, or to compare the efficiency of different sources in supplying nutrients or toxic elements to plants. However, plant analysis is more difficult to interpret in field experiments. Only if very deficient soils are used to compare nutrient sources can significant differences in nutrient contents in leaves or other parts of plants be expected.

PRODUCT AND NUTRIENT EVALUATION

Fertilizers are often compared for their main nutrient and in such cases the problem is nutrient evaluation. This is often the case of N in organic fertilizers and P in phosphate rocks.

Product evaluation is the simplest type of fertilizer evaluation and it is used without the concern of specific effects of nutrients, as is the case of comparing multinutrient organic fertilizers. It can be used in preliminary trials, but there are disadvantages for more detailed evaluations, as pointed out by Terman and Engelstad (1971). Often poorly defined fertilizers are compared in such a manner and then only if the factors associated with yield increases cannot be isolated. This is sometimes the case with very complex organic sources, in which it is difficult to evaluate the effect of the individual nutrients and of the organic matter on yields, especially under field conditions. Even in complex fertilizers the effect of the nutrients can often be isolated. Erp and Dijk (1992), using a pot experiment, were able to isolate the individual effects of N, P and K of processed pig slurries on the uptake of the nutrients by plants.

Whenever possible, the direct nutrient evaluation should be preferred, equalizing the additions of the nutrients not being evaluated between treatments. Effects not due to nutrients, such as conditioning of physical soil properties and change of the soil reaction, should also be evaluated and this is often possible by carefully designed experiments.

GREENHOUSE AND FIELD EXPERIMENTS

Greenhouse and field experiments are important for the agronomic evaluation of fertilizers

Pot experiments conducted in greenhouses present some advantages for fertilizer evaluation, such as the possibility of the control of environmental factors, and the selection of soils that are deficient in the nutrient to be evaluated. Greenhouse experiments are often sufficient to reach conclusions about the possibility of the use of fertilizers. Chien and Hammond (1991) were able to show clearly, through a pot experiment, that calcined phosphates were inferior, from the agronomic point of view, to uncalcined phosphates. Terman and Allen (1967) could demonstrate, in pot experiments, the conditions of efficient use of under-acidulated phosphates.

The soils for greenhouse experiments to evaluate nutrient sources must be deficient in the nutrient under test. Other factors that can limit plant growth, such as soil acidity and nutrient deficiency must be corrected, so that, as much as possible, the major source of variation in growth can be related to the nutrient in the fertilizers evaluated. Standard nutrient sources are used as reference, such as triple superphosphate for P and ammonium nitrate for N. Nutrients not being tested should be supplied in adequate amounts. It is important to supply N and K, the two macronutrients required in the largest proportions by plants, on the basis of expected yield of dry matter. Details on greenhouse techniques for fertilizer evaluation are described by Allen *et al.* (1976). Pot experiments with fertilizers are often more laborious than field experiments. Especially watering must be done with care, requiring daily attention to avoid excesses.

Most pot experiments used for the evaluation of nutrient sources can be designed as randomized complete blocks with three or four replicates. It is important to compare two or more rates of each nutrient source, although in cases of the comparison of too many sources, a single rate can be used for a preliminary selection of the most promising alternatives. The amount of nutrients added in experiments is usually based on the total contents of the nutrients in the fertilizers. The parameter that best expresses the availability of the nutrients supplied is the nutrient uptake, normally considering the aboveground part of plants. For elements that are not nutrients, such as some heavy metals, total plant uptake can also be considered. Alternatively, nutrient contents in plants or relative yields of dry matter are also used as indexes of the nutrient availability.

Results of pot experiments can be used to compare nutrient sources, but in general extrapolation to field conditions should not be made. In general, pot experiments give a better differentiation between sources than field experiments. Field experiments provide the quantitative relations between applied rates of the nutrient and yields, necessary for economical evaluation. They are also important for the evaluation of long term residual effects. Smith (1985), using multiple rate experiments and growing silage maize during three years, could represent the N recovered from rainbow trout manure in terms of equivalent ammonium nitrate N. Mahler and Hemamda (1993) determined the value as N fertilizer of several organic residues applied to wheat. Mascagni and Cox (1985) compared the immediate and residual effects as well as placement of several manganese sources for soybeans.

As in the case of pot experiments, in field experiments it is also necessary to correct unfavourable soil conditions, such as acidity, and supply the nutrients needed by the crop, so as to favour the nutrient being tested as the major source of variation of differences in yields due to the treatments. Multiple rates of nutrients should be applied to allow the comparison of sources. For field experiments the yields of the parts of the crops that are normally harvested are considered.

Qualitative and quantitative statistical analysis should be used to compare nutrient sources. In addition, mathematical models can be used to calculate indexes used to evaluate the agronomic efficiency of fertilizers.

MATHEMATICAL MODELS

Many types of indexes to compare nutrient sources have been used, with some variation in representation (Terman and Engelstad, 1971; Goedert *et al.*, 1986; Chien *et al.*, 1990). Two very common indexes are the relative yield increase (RYI) and the nutrient equivalent in relation to a standard nutrient source (NE). These two concepts can be expressed by the following equations:

$$RYE = \frac{Y_2 - Y_1}{Y_3 - Y_1} \times 100 \qquad \textbf{(1)}$$

TABLE 1
Maize yields obtained by the use of ordinary superphosphate and alvorada phosphate rock and calculated values of the RYE and NE indexes

P_2O_5 applied kg/ha	Yield		RYE %	NE %
	Superphosphate kg/ha	Phosphate rock kg/ha		
0	1412	1412	-	-
60	4338	3327	65	56
120	4916	3636	63	40
2nd degree polynomial:				
a_0	1412	1412		
a_1	68.33	45.30		
a_2	-0.3261	-0.2231		

$$NE = \frac{X_1}{X_2} \times 100 \tag{2}$$

Y_1 is the production obtained without application of the nutrient, Y_2 is the production given by the source being tested and Y_3 is the production of the reference source of the nutrient. Thus the relative yield increase represents the percentage of yield increase obtained by a source being tested in relation to the yield increase obtained with the same rate of the nutrient applied as the standard source.

The nutrient equivalent is calculated by equation 2, considering X_1 the nutrient rate of the standard source that produces the same yield of the rate X_2 of the nutrient supplied by the tested source.

Equation 1 is considered a vertical comparison whereas equation 2 represents a horizontal comparison (Chien *et al.*, 1990). These expressions are convenient for comparison and ranking of the agronomic efficiencies of several sources of nutrients in relation to a standard source.

Equations 1 and 2, based on the comparison of a single rate of a nutrient source with a single rate of a standard source, taken from a response curve in the last case, have some limitations. They assume that the yield response is linear with increasing amounts of applied nutrient. However, yield response is invariable curvilinear over much of the response range and single rate comparisons might result in different evaluations, depending of the position on the response curves, especially if the shapes are different for the fertilizers compared (Terman, 1967).

Thus when more detailed comparisons of nutrient sources are needed, it is advisable to obtain experimental response curves and adjust curvilinear mathematical models, such as polynomial and exponential equations (Terman and Engelstad, 1971; Nelson *et al.*, 1985). To illustrate some economical concepts, the second degree polynomial will be considered in this paper.

The concepts represented by equations 1 and 2 will be illustrated by a numerical example from a field experiment comparing a phosphate rock with superphosphate for maize (Gomes *et al.*, 1961). In Table 1 the experimental results are presented and also the coefficients of the second degree polynomial adjusted to the data. The values presented of the RYE are calculated directly from the data. To calculate the value of the NE, the value of the yield for the phosphate rock is compared with the second degree polynomial for superphosphate and the equation solved to find X_1. For example, for $X_2 = 60$, X_1 is 33.3, which results in the 56% value of the NE.

ECONOMIC EVALUATION

A response curve of a crop to applied fertilizer rates can be expressed by the second degree polynomial:

$$Y = a_0 + a_1 X + a_2 X^2 \qquad (3)$$

The economically optimum rate of the nutrient is given by:

$$X_e = \frac{R - a_1}{2a_2} \qquad (4)$$

where R is the c/v ratio, c and v representing, respectively, the unit cost of the nutrient and the unit value of the agricultural product. To make the examples more general, c and v can better be expressed in terms of kilogrammes of yield product instead of currency.

Equations 3 and 4 can readily be used to make economical comparisons of nutrient sources with available response curves and information on the cost of the fertilizers and the value of the agricultural product. Considering the example given in Table 1 and a c/v ratio (R) for 1 kg maize and 1 kg $P_2 0_5$ of 8 for superphosphate and 3 for the phosphate rock, the profit for the optimum economical rate will be of 2791 kg/ha maize for superphosphate and 2006 kg/ha maize for the phosphate rock.

One of the problems of the economical evaluations of alternative nutrient sources is the non-existence of commercial prices. In such cases the minimum conditions for a fertilizer to be economically competitive with a standard fertilizer can be calculated. Two aspects determine the economy of use of the alternative source: the saving made by using a cheaper fertilizer and the decrease in production caused by the use of the less efficient fertilizer (Raij, 1986).

Assuming X as the economically optimum rate of the nutrient supplied by the standard fertilizer (s), the limiting condition for an alternative fertilizer (f) to become economically competitive with the standard source is given by:

$$R_s X - R_f X > Y_s - Y_f \qquad (5)$$

The terms of both sides of equation 5 are expressed in yield values and not actual currency. Such representation has the advantage of being more general, allowing comparisons at different times in countries with high inflation rates and between countries with different currencies.

The equation that limits the minimum production of a fertilizer in relation to a standard source is given by:

$$Y_f = a_0 + [a_1 - (R_s - R_f)]X + a_2X^2 \tag{6}$$

Considering the response curve for superphosphate of Table 1 and a value of $R_s = 8$ and assuming that an alternative phosphate would cost half the price or have a c/v ratio of $R_f = 4$, the yield predicted for the economically optimum rate of P_2O_5 of the superphosphate is of 4947 kg/ha maize. For the alternative phosphate, the minimum yield allowed to avoid losses would be of 4575, meaning that the value of RYE should be at least 89%.

Equation 6 can also be used to simulate other possibilities when prices of alternative nutrient sources are not known, establishing minimum conditions for such products to be economically competitive with the standard source (Raij, 1986). Somewhat similar calculations were made by Bekele and Höfner (1993), using relative concentrations.

In practice one may face dilemmas. Often the shapes of the response curves of the different fertilizers compared are not the same. In such cases it might be useful to make comparisons at different rates of the nutrient. On the other hand the impossibility to reach precise conclusions with experimental data on fertilizer application for crops should be kept in mind. Differences in yield responses to fertilizers for different soils or between different years for the same soil are often so large that any improvement reached by the choice of a model with a better adjustment is easily surpassed by the experimental error.

DISCUSSION

Alternative sources of nutrients to the commercial fertilizers will continue to be a subject of interest. With the change of policies of many countries towards more open trade, the search for local sources of nutrients, often more expensive to use, may slow down. On the other hand, there is an increasing pressure to apply a variety of residues on soils. Recycling of many types of materials through soils is an increasing tendency. Hence, agronomists will have to define the rules for making the best use of nutrient and organic matter sources for the improvement of the productivity, without contaminating the soils with hazardous elements.

There is a long way to go to get things done in an organized way that might lead to practical implementation. For example, there are decades of information accumulated on the use of phosphate rocks, but even so, agronomists still seem to have serious difficulties in handling the subject. The same happens with organic sources, known to be in general excellent for agricultural use, but there is still a need for a more organized effort to evaluate properly such products as fertilizers.

An integrated nutrient management for crop production requires that quantitative information on all nutrient sources be made available. In the case of local sources there is still a need to at least organize existing knowledge for local implementation.

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Integrated plant nutrition in Zimbabwe

Two major constraints to good crop production are low rainfall and low soil fertility. The resource-poor small-scale farmers are heavily concentrated in the low rainfall areas and can often not afford to purchase fertilizer for expected low yields. Therefore, cost reduction in the amount of purchased fertilizer achieved through integrated plant nutrient supply is likely to be most beneficial for them.

Since maize is the staple food crop of Zimbabweans it is grown in most areas of the country. Its production under dryland conditions is highest in natural regions IIa and IIb, where rainfall is more reliable compared to regions III, IV and V. Vincent and Thomas (1961) indicated that cropping should be carried out in natural regions I, IIa and IIb with livestock becoming increasingly important in regions III, IV and V.

Appropriate research on fertilizer recommendations in the communal areas, where about 70% of the people live, has not yet been carried out. However, farmers are using manure supplemented with N fertilizer or, increasingly, compound fertilizers in the place of manure. The rates of manure applied as well as their effectiveness have been determined only in a few areas. The objective of this paper is to try and highlight some of the cheaper integrated plant nutrition practices as well as those with the potential for reducing the high cost of chemical fertilizers needed for crop production in Zimbabwe.

MATERIALS AND METHODS

Survey of manure application rates and supplementation with chemical fertilizers

In 1984 a survey was made to determine the rates of manure application, as assessed from manure piles in the fields, in the Chihota and Svosve communal areas. Twenty six fields were sampled in Chihota and ten in Svosve. The selection of the fields sampled was based on apparent evenness of the height, diameter, shape and row spacings of the manure piles and also distances between the fields. The localities sampled were at least 5 km apart and, whenever possible, the nearby fields were sampled in each locality (see Mugwira and Shumba, 1986).

Manure samples taken from the piles in the fields were ground to pass through a 2 mm sieve and were applied to a sandveld soil from Chihota to evaluate their effect on plant growth in a greenhouse. This soil had low initial fertility as described previously (Mugwira and Mukurumbira,

PAPER 4.7

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1984). Each manure was applied to three pots containing 7 kg of the soil at the rate equivalent to that estimated from the field survey on weight basis. The treated soils were placed in plastic pots and planted to maize variety R201, in the greenhouse. The effects of the manure applications were also evaluated from the fields where the application rates had been estimated. Cobs were taken randomly from the manured fields and from portions of the same fields or adjacent fields which had not received manure for at least two years. The cobs were weighed before and after shelling to determine cob size and grain yield. The farmers were also asked if they had topdressed the maize in the currently manured fields with N fertilizer.

Trials on supplementing manure with fertilizers

Greenhouse experiments

Greenhouse experiments were conducted to determine the effects of supplementing low-nutrient manures with different fertilizers on plant growth. The first of these experiments showed that the addition of N, P, K or S to low-nutrient manures, to bring the total level of each of these manures to the same level as high-nutrient manure, increased plant growth only when N had been applied. In the second experiment, in which all possible combinations of N, P, K and S were used, it was found that all treatments which also included P were more effective. Similar results were obtained in the third experiment which also indicated that N, P, K or S, added to manure at their levels in the recommended compound D fertilizer rate, did not significantly affect plant growth. The results of these experiments showed the importance of supplementing low-nutrient manures with N and P as underscored by the fact that NP treatments were generally as good as N, P, K, S or compound D. Therefore, field trials were conducted with supplementing manure with chemical fertilizers.

Field experiments

Field trials have been conducted to evaluate the effects of manure, compound fertilizer (8% N, 14% P_20_5 and 7% K_20) and N topdressing on the yields of continuous maize grown on sandy soils in three communal areas since 1983/84. The design was a 3x3x2 factorial of three manure rates (0, 7.5 and 15 t/ha), applied biannually, compound fertilizer rates (0, 150 and 300 kg/ha) and two levels of N topdressing (40 and 80 kg N/ha). The treatments were arranged in a completely randomized block using four replications. Manure was spread on the surface and ploughed under before planting. Compound fertilizer was spot placed using fertilizer cups at planting.

Hybrid maize R215 was planted at spacings of 90 cm x 45 cm in plots measuring 6 m x 5 m. The plots were weeded by hoes. Sidedressing of ammonium nitrate was done at six weeks after planting. Yields were determined at harvest from net plots of 4 m x 3 m. Typical results from a site in one (Chihota) of the communal areas are discussed in this paper.

Biological nitrogen fixation in crop rotation

Field trials on biological nitrogen fixation (BNF) are being conducted to evaluate the effects of different grain legumes on the following maize crops. These trials are being conducted at different locations in the different agro-ecological zones. In their 'maize' season, all plots receive 100 kg P_2O_5 plus 80 kg K_20 per hectare applied as single superphosphate and potassium chloride respectively. Crop residues from the previous season are ploughed under. Nitrogen is applied as ammonium nitrate at four rates of 0, 60, 120 and 180 kg N/ha in three equally split applications. These trials have been conducted at various sites since 1985/86.

Rhizobium ecology

Rhizobium ecology studies were started in the 1987/88 season to study the effects of indigenous rhizobial populations on the response of the different grain legumes, viz sugar beans, cowpeas, groundnuts and soybeans, to inoculation with exotic strains at five sites (CSRI, 1988/89). The following year trials were residually cropped to evaluate the persistence of inoculation (check) vs. inoculation vs. fertilizer nitrogen. The inoculation treatments consisted of a mixture of three suitable *Rhizobium* strains dribbled into the furrows at sowing, while the fertilizer nitrogen (AN) was applied by broadcasting an equivalent of 150 kg N/ha at planting followed by another 150 kg N/ha at flowering. Basal fertilizer was applied according to fertilizer recommendations. Whole plant samples were collected at mid-flowering for the determination of plant growth, nitrogen uptake and nodulation (numbers and mass). Groundnuts were top dressed with 200 kg/ha of gypsum at the time of sampling. Grain and stover yields and nitrogen uptake were assessed at harvest. Results from the two most contrasting soils are reported in this paper.

Evaluation of phosphatic fertilizers

This experiment was carried out to evaluate the agronomic effectiveness of Dorowa phosphate rock (DPR), which is locally available in the country, with a partially-acidulated phosphorus rock (PAPR) made from DPR (25% acidulation with H_2SO_4) relative to double superphosphate (DSP) at two sites. The relative responses of maize and wheat to these materials in relation to soil properties which influence the dissolution of DPR materials in the two soils were determined.

The field experiment was carried out at Shamva and Marondera. Shamva soil is a clay loam derived from mafic rocks and Marondera soil is a sandy soil derived from granitic parent material. The land was prepared and planted with maize to deplete nutrients a year before the experiment was started. Soil samples were taken for soil analysis and all stover was removed from the field before planting each crop.

A randomized complete block design was employed and the plot size was 22.5 m^2. The test crops were the SR 500 variety of maize *(Zea mays* L.), alternating with Sengwa and a variety of wheat (*Triticum vulgares* L.).

The DPR, PAPR and DSP materials ground to pass a 150-μm sieve were applied to plots in three replications before planting in the first year. The following basal fertilizers were applied before planting each crop: 138 kg N/ha as ammonium nitrate (34.5% N), 40 kg K_2O/ha as muriate of potash (60% K_2O), and 141.1 kg $CaSO_4$/ha as (gypsum, 17.5% S). The P and S rates were balanced throughout the experiment.

The fertilizers were broadcast evenly on the plots and worked into the soil to a depth of 5 cm before the seed was planted. Maize seeds were planted in rows 90 cm apart and 45 cm within each row and four seeds were dropped at each station and thinned to two at 10 days after planting. The wheat rows were 25 cm apart and sowing was by drilling along the rows; seedlings were thinned to two at 10 days after planting. The plots were irrigated immediately after planting. Maize cobs were harvested from a plot area of 11.1 m^2 and wheat grain from 1 m^2.

To compare the yields, the least significant difference (LSD) test and Duncan's Multiple Range Test (DMRT) procedures for comparing means of treatments were used. To compare the agronomic effectiveness of DPR and PAPR materials with respect to DSP, the Relative Agronomic Effectiveness (RAE) was calculated using the formula of Engelstad *et al.* (1974) as follows:

TABLE 1

Fertilizers applied and maize varieties used in manured and unmanured fields in two communal areas in 1984/85

Fertilizer and maize variety	% of total farmers	
	Manured	Unmanured
Fertilizer "D" (8-14-7)	21.4	50.0
Top dressing AN	89.3	75.0
Variety R201	36.0	34.7
R215	40.0	52.2
SR52	8.0	4.3
Farmer's seed		8.7

TABLE 2

Complementary effects of manure and chemical fertilizers on maize yield (t/ha) in a communal area (Chihota)
(Source: CSRI, unpublished data)

<table>
<tr><th>Fertilizer</th><th>No manure</th><th>Manure</th><th colspan="3">Increases (%)</th></tr>
<tr><td colspan="6">Nitrogen topdressing</td></tr>
<tr><td>40 kg N/ha</td><td>2.26</td><td>3.97</td><td colspan="3">76</td></tr>
<tr><td>80 kg N/ha</td><td>3.74</td><td>6.08</td><td colspan="3">62</td></tr>
<tr><td>Gross effect</td><td>(6.08/2.26)</td><td></td><td colspan="3">169</td></tr>
<tr><td colspan="6">Basal compound</td></tr>
<tr><td>Compound D</td><td>None</td><td>2.08</td><td>4.16</td><td>100</td><td></td></tr>
<tr><td>Compound D</td><td>150 kg/ha</td><td>3.74</td><td>8.64</td><td>132</td><td></td></tr>
<tr><td>Gross effect</td><td>(8.64/2.08)</td><td></td><td></td><td>315</td><td></td></tr>
</table>

Note: 40 kg N/ha represents (No N) modified from preliminary trial where no N was not acceptable to the farmer.

$$RAE = \frac{Yield\ \ with\ \ PR - (\ yield\ \ of\ \ control\ )}{Yield\ \ with\ \ DSP - (\ yield\ \ of\ \ control\ )} * 100$$

RESULTS AND DISCUSSION

Manure survey

The rates of manure applied to the fields were variable in each communal area, averaging 35 t/ha or 57 m^3/ha in Chihota and 39 t/ha or 64 m^3/ha in Svosve. These data indicate that on average 1 m^3 of manure weighed 0.61 tonnes in both Chihota and Svosve. The average increases in the total dry matter yield of the greenhouse crops caused by the manure applications were 364% and 68% with Chihota and Svosve samples, respectively, over the control with no manure added. The N content in the manures was not correlated with grain yields. It was also noted that about 89% of the manured farmers topdressed their manured fields with ammonium nitrate (Table 1).

Supplementation of manure with chemical fertilizers

There was a complementary effect of manure and fertilizer on maize yield (Table 2). The gross yield increment of 169% from these two inputs was slightly greater than the sum total of each input, 76% for manure and 75% for N (40 kg N/ha taken as baseline for low). Yield increment from the application of compound fertilizer (79%) was higher than that from the application of N (65%) when no manure was applied. Furthermore, the yield increment from the combined effect of manure plus compound D (315%) was much higher than that from manure plus N. These two trends indicate that once the N requirement of the crop was met, other nutrients supplied in compound D such as the chronically deficient P in these soils, provided extra in-crease in yield. These results also show that the normal target yield of about 4 t/ha under these conditions was achieved by supplying 80 kg N without manure, 40 kg N with manure, manure alone or compound D alone. The principle of integrated nutrient supply is underscored by the much higher yields obtained when manure was supplemented with N or compound fertilizer.

Biological nitrogen fixation in crop rotation

Following the legumes grown in the 1985/86 season, maize grain yields were increased by rotating legumes and maize at all sites. However, the effect was significant at only one site (Table 3). As shown by these data, increasing rates of nitrogen fertilizer also increased grain yields in the high (above 700 mm) rainfall areas but the effect was much less in the lower rainfall areas.

Stover yields were also significantly improved by returning legume crop residues to the soil, but this effect was not affected by rainfall as in the case of the grain. Because organic matter levels in most communal (small-scale cultivated) fields are in the range of 0.30-0.40% in the 0-15 cm plough layer, the crop residues in the experimental fields recycled continually. In the cropping season in which the above data were obtained, only previous fallowing resulted in significantly higher soil organic matter content than in plots where maize had been grown in 1985/86.

Rhizobium ecology

Although grain and stover yields were not affected by the N, their N concentrations were significantly increased by inoculation with rhizobium and application of N fertilizer on Chibero soil with low initial N (Table 4). It is also noted that the total N uptake was greatly enhanced by inoculation. These results contrasted with those at Grasslands with high initial N and an abundance of indigenous *Rhizobium* such that the nitrogen treatments had no effect on the measured parameters (Table 5).

Phosphatic fertilizers

Application of different rates of DSP,PAPR and PR materials did not significantly affect maize or wheat yield on the red clay at Shamva. This soil had a high pH, high exchangeable Ca, and a moderate resin-extractable P of 16 ppm (Nleya and Syers,1992).

On the acid sand at Marondera DSP20, DSP40 and DSP80 gave significantly higher maize yield than the control but only DSP80 was superior to the other P treatments (Table 6). Wheat following a maize crop on this sand also produced higher yield from the application of DSP and PAPR than from the other P treatments. Although DSP80 did not perform better than the freshly-applied DSP20 and DSP40, it had higher residual effect. PAPR gave yields similar to those of DSP20.

In the second year (1990/91) the P treatments significantly increased maize yield except for the ineffectiveness of DPR160 and DSP20+DPR140 (Table 6).

TABLE 3

Effects of crop rotation and nitrogen application on maize grain and stover yield at Ushe (Chihota) in 1986/87
(Source: CSRI, 1986/87)

Previous crop (grain t/ha)					
Nitrogen applied (kg/ha)	Fallow	Maize	Groundnuts	Cowpeas	Mean
Previous crop (grain t/ha)*					
0	3.57	1.99	3.74	4.26	3.39
60	3.95	2.75	4.33	3.79	3.70
120	4.64	3.41	4.33	4.21	4.15
180	4.16	3.32	4.81	4.07	4.09
Mean	4.08	2.87	4.30	4.08	
Stover (t/ha)**					
0	3.52	2.27	3.38	3.48	3.16
60	3.44	2.60	3.72	3.72	3.37
120	3.98	3.03	3.56	3.87	3.61
180	3.47	2.85	3.81	3.74	3.47
Mean	3.60	2.69	3.62	3.70	

* LSD for previous crop : 5% = 0.88; 1% = 1.27; 0.1% = 1.86
LSD for N rate : 5% = 0.48; 1% = 0.64; 0.1% = 0.85
LSD for N x crop : 5% = 0.96; 1% = 1.29; 0.1% = 1.70

** LSD for previous crop : 5% = 0.72; 1% = 1.03; 0.1% = 1.52
LSD for N x crop : 5% = 0.99; 1% = 1.32; 0.1% = 1.75

Basal fertilizer was 100 kg P_2O_5 plus 80 kg K_2O per hectare.

In 1990/91 RAE values for maize and wheat showed that PAPR was very effective on the sand. In the second year PAPR had the higher RAE values than all the other treatments. The results also suggest that 80 kg P/ha DPR material could be a suitable rate for this soil and that higher yields may be expected by adding a little water-soluble P to DPR.

CONCLUSIONS

The survey showed that communal farmers are acutely aware of the need to integrate sources of plant nutrients as some 20% of them apply NPK and 90% apply N to their manured crop. Results from the survey and field trials suggest that such supplementation of manure with N usually increases maize yields by 60-80%. Supplementing the manure with compound (NPK) fertilizers may increase yield by as much as four-fold. Research from biological nitrogen fixation (BNF) trials have further supported the use of combined locally available or cheap sources of nutrients. It has been shown that when the right *rhizobium* is properly inoculated the benefits can be as great as those obtained when 300 kg N is applied. More importantly, BNF has shown that this benefit in N economy is greatest on the nutrient-depleted sands commonly found in the communal areas. There is evidence that the inclusion of soluble P sources such as double superphosphate with PR may increase the dissolution of PR on the predominant acid sandy soils. Therefore, results of research suggest the use of locally available PR in maize-legume rotations has the potential of further reducing cost of purchased fertilizer for resource-poor farmers.

TABLE 4

Effects of nitrogen source on the N content and N uptake of grain legumes at Chibero (low initial soil N)
(Source: CSRI, 1988/89)

	Crops				
N source	Bean	Cowpea	Groundnuts	Soybean	N source mean
	Grain N content g N/kg				
0	29.3	36.1	36.1	46.9	37.1
Inoculant	30.4	36.0	36.0	56.1	39.6
AN	34.3	38.3	38.3	54.4	41.3
Mean	31.3	36.7	36.7	52.4	
	Stover N content g N/kg				
0	8.5	13.3	12.4	5.5	9.9
Inoculant	10.8	13.7	12.8	8.6	11.4
AN	14.1	18.5	14.4	7.2	13.5
	11.1	15.2	13.2	7.1	
	N uptake kg N/ha				
0	6.8	54.3	32.1	17.1	27.5
Inoculant	7.2	46.6	38.2	47.7	34.9
AN	4.8	52.9	35.8	62.0	38.9
	6.2	51.3	35.4	42.3	

LSD (0.05) values for	:	N source	Crop
Grain N content	:	1.8	2.2
Stover N content	:	1.5	2.5
N uptake	:	NS	29.6

Basal fertilizer was 120 kg P_2O_5, 80 kg K_2O,).5 kg Mo and S kg B per hectare.

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TABLE 5
Effects of nitrogen source on the N content and N uptake of grain legumes at Grasslands (high initial soil N)
(Source: CSRI, 1988/89)

	Crops				
N source	Bean	Cowpea	Groundnuts	Soybean	N source mean
			Grain N content g N/kg		
0	29.3	36.5	40.5	62.5	42.2
Inoculant	29.0	39.5	41.5	64.0	43.5
AN	30.3	39.3	43.3	64.0	44.2
	29.5	38.4	41.8	63.5	
			Stover N content g N/kg		
0	8.3	16.3	16.0	9.0	12.4
Inoculant	8.0	16.3	15.8	12.0	13.0
AN	8.5	20.0	18.8	11.3	14.6
	8.3	17.5	16.8	10.8	
			N uptake kg N/ha		
0	24.7	28.9	69.5	257.2	95.1
Inoculant	27.8	47.4	67.8	246.2	97.3
AN	36.6	32.3	64.8	280.7	103.6
	29.7	36.2	67.4	261.4	

LSD (0.05) values for :	N source	Crop
Grain N content :	NS	2.7
Stover N content :	NS	1.9
N uptake :	NS	34.1

TABLE 6
Maize and wheat yields as affected by the various treatments at Marondera site (t/ha)

	1989/90		1990/91
Treatment	Maize	Wheat	Maize
DSP 80	6.91 a	5.90 a	6.60 a
DSP 40	6.07 ab	5.45 a	6.43 a
DSP 20	5.79 ab	5.01 a	6.23 a
DSP 20+DPR 60	5.62 abc	4.28 b	5.67 a
PAPR 160	5.35 bc	4.90 a	5.93 a
DPR 40	5.33 bc	3.60 c	5.60 a
DPR 80	5.16 bc	3.98 c	5.62 a
DPR 80R	5.06 bc	3.88 c	5.47 a
DPR 160	4.91 bc	4.23 b	5.03 b
DSP 20+DPR 140	4.69 bc	4.10 b	4.23 b
Control	3.89 c	3.54 c	4.23 b

In each column, treatments with the same letter are not significantly different at the 5% level of the Duncan Multiple Range Test (DMRT).

SESSION 5

Plant nutrient management in farming systems and in watersheds and territories

Plant nutrient balance sheets in lowland rice-based cropping systems

An understanding of the rate of applied nutrients and their effect on rice and rice-based cropping systems is required in developing practices to improve nutrient use efficiency. It is critical that integrated nutrient management is studied to sustain and improve soil fertility in lowland rice-based cropping systems. Great opportunities exist for increased rice production through increased application rates and improved management of mineral fertilizers and through integrated nutrient management using mineral and organic fertilizers in rice-based cropping systems.

In lowland rice, the grain yields of modern rice increase when plant nutrients, deficient in the soil, are added. To increase nitrogen use efficiency, several methods are available. They include proper nitrogen application methods with good water management, soil placement of urea and modified urea fertilizers and the use of controlled release and slow release nitrogen fertilizer materials. Rice varieties also differ in their ability to recover fertilizer nitrogen. Management practices to alleviate phosphorus deficiency depend largely on soil characteristics, water regime, cropping intensity and cropping systems. Literature suggests that sulphur deficiency has been reported from many rice-growing countries and areas with zinc deficiency have greatly increased. Technology is available for correcting both of these nutrient deficiency problems. Considering limited economic endowments of rice farmers in the regions, the introduced technology should be both highly productive and profitable.

In some areas of the world, rice yield increases have been substantiated with new production technology. Some of this new technology has resulted in an increase of cropping intensity, which places demands for more nutrients to sustain productivity. For example, a single irrigated lowland rice crop producing 9.8 t/ha of grains and 8.2 t/ha of straw in about 115 days took up 218 kg of nitrogen, 31 kg of phosphorus, 258 kg of potassium, and 9 kg of sulphur (De Datta, 1985). These, and other nutrients removed by the crop, must be replenished to sustain high rice production. India, China and Viet Nam successfully use green manure in the cropping systems of their major cereals. In India, a legume crop such as mung bean or cowpea is incorporated into rice-rice or rice-wheat cropping systems to improve physiological energy output (Pillai, 1983). China has been using a cropping systems concept to sustain intensive cropping with high output using legumes in rotation with cereals. Organic and

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PAPER 5.1

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inorganic nutrient sources and their management are also being integrated in rice-based cropping systems (Guo, 1986).

Results from recent studies on integrated nutrient management and plant nutrient balance sheet in rice and rice-based cropping systems are summarized here.

NITROGEN

Asia is now the largest and fastest growing nitrogen market in the world. Annual consumption rates in China, India, Pakistan, and Indonesia, among the Asian countries, now take up more than 14% of the already large consumption base (Stangel and De Datta, 1985). This rapidly growing production and consumption of nitrogen fertilizers are important developments in the region. But unless high nitrogen losses and low fertilizer efficiency are prevented, most of the potential benefits from increased nitrogen fertilizer use may not be realized. The following sections summarize information on relevant research on nitrogen fertility of rice soils and on fertilizer management for efficient use in lowland rice.

Soil nitrogen

Many chemical and biological processes influence nitrogen availability in lowland rice soils. Mineralization of organic nitrogen in flooded soils largely depends on the chemical environment and soil microbiological population. Nitrogen supplied by the soil has been repeatedly shown to be sufficient in achieving substantial yields provided other production practices are at optimum levels.

Under some conditions, up to 3 t/ha of grain yield have been consistently obtained without nitrogen fertilizer. With increased research on soil nitrogen and its management, substantial production gains are possible with resources already on land.

The available nitrogen status in lowland rice soils is influenced by many factors. In some soils, nitrogen mineralization may proceed at a slower rate in flooded than in non-flooded soils. However, the reverse relationship has also been observed in many soils with different chemical and biological environments (Patrick and Wyatt, 1964). In flooded soils, the product of mineralization is mainly ammonium.

Nitrogen exists in three major fractions: ammonium in soil solution; ammonium in exchange sites; and ammonium in non-exchangeable form

Ammonium nitrogen in soil solution and at exchange sites is readily available to the rice plant, whereas reports on the availability of non-exchangeable ammonium are conflicting. The release of non-exchangeable (fixed) NH_4^+ and the importance of exchangeable NH_4^+ at planting in lowland rice soils (initial exchangeable NH_4^+) for rice growth was reported by Mengel *et al.* (1986). Their conclusion was that initial exchangeable ammonium behaved like fertilizer nitrogen and this may serve as a valuable guideline for nitrogen fertilizer application rates when computed on a hectare basis. Results from Keerthisinghe *et al.* (1985) showed that NH_4^+ contributions from non-exchangeable form occurred only in a silty clay loam soil rich in vermiculite. On all soils, the exchangeable soil NH_4^+ was depleted during the first eight weeks of rice growth, indicating that their fraction was easily available to the rice crop. Nevertheless, these studies indicate that non-exchangeable NH_4^+ may play a major role in the nitrogen nutrition of rice crops grown in lowland rice soils rich in vermiculite (Keerthisinghe *et al.*, 1985).

Biological nitrogen fixation (BNF)

One approach taken in N balance studies is where balance is defined as the difference between easily measurable output (N in the exported parts of the plant and soil N at the end of the experiment) and inputs (N fertilizer applied and soil N at the beginning of the experiment). In such experiments, N losses by leaching, denitrification and volatilization, and atmospheric deposition are not recorded. Therefore such balance values usually provide an under-estimation of BNF during the crop cycle (Roger and Ladha, 1992). N balances in long-term fertility experiments range from 19 to 98 kg N/ha per crop (average of 50 kg N/ha) in fields with no fertilizer N applied. A compilation of balance experiments with rice soils shows an average balance of about 30 kg N/ha per crop in soils where no inorganic fertilizer N was applied. Table 1 shows the range of estimates of N_2 fixed by various agents in lowland rice fields (Roger and Ladha, 1992).

Recently, Kundu and Ladha (1993) reported relative BNF contributions in the Philippines were between 59 and 103 kg N/ha per year whereas in Japan it was reported to be between 19 and 38 kg N/ha per year. The balance sheet, however, indicates very little gain and even net losses of N under fertilizer N treatment, which are attributed more to the loss of applied fertilizer N than the smaller BNF contribution.

The same authors, Kundu and Ladha (1993), suggest three distinct ways to improve efficient management of soil N in lowland rice.

Drying of rice fields in the pre-rice season

Several factors may contribute to the N flush due to mineralization that follows rewetting dry soils (Buresh and De Datta, 1991). Recent research results suggest that drying and rewetting not only generate an N pool but also increase the mineralization rate with more stable N pool in the soil (Cabrera, 1993). Furthermore, in tropical lowland rice, soil and crop management practices during the dry season should be designed to limit NO_3^- build-up so as to replace NO_3^- that is prone to loss during the dry-to-wet transition (George *et al.*, 1992). This system, to become viable in rice production systems, will need strategic soil and crop management research with strong economic analysis.

Conservation and recycling of nitrate N formed during soil drying

Drying of soil following the harvest of a flooded rice crop favours formation of nitrate N. This nitrate gets lost rapidly (Figure 1) after soil flooding, through leaching, and denitrification. Recently, Buresh and De Datta (1991) and George *et al.* (1992), have observed a positive role for the green manure legume *Sesbania rostrata* in the conservation and recycling of soil nitrate.

Use of subsoil nitrogen

In continuously flooded puddled fields, rice plants largely fail to make use of N from deeper soil layers due to the formation of a hard impervious pan below the surface soil, in some cases, and because of a negligible water percolation rate in others (Kundu and Ladha, 1993). Sharma *et al.* (1988) reported significant positive correlation between subsoil root density and rice grain yields. Increased rooting depth was believed to be exploiting a greater N pool from deeper soil layers.

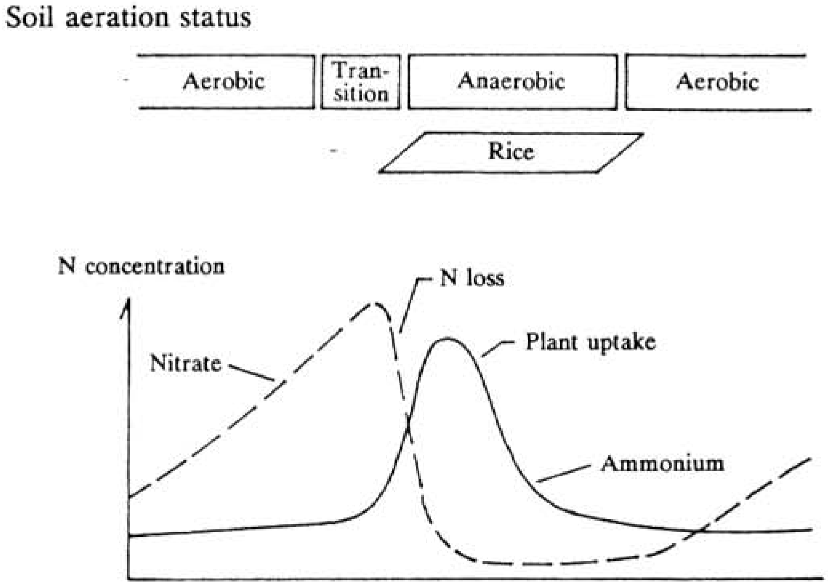
TABLE 1

Range of estimates of N_2 fixed by various agents in wetland rice fields (kg N/ha/crop) and theoretical maximum potential (value and assumptions) (adapted from Roger and Ladha, 1992)

Component	Reported range of estimates	Theoretical maximum potential and assumptions
BNF associated with rice rhizosphere	1-7 kg N/ha per crop	40 kg N/ha per crop * All rhizospheric bacteria are N_2-fixers, * C flow through rhizosphere is 1 t/ha per crop, * 40 mg N is fixed g/C.
BNF associated with straw	2-4 kg N/t per straw	35 kg N/ha per crop * 5 t of straw is applied, and * 7 mg N is fixed g/straw.
Total heterotrophic BNF	1-31 kg N/ha per crop	60 kg N per crop * All C input (2 t/crop) is used by N_2-fixers.
Blue-green algae	0-80 kg N/ha per crop	70 kg N/ha per crop * Photosynthetic aquatic biomass is composed exclusively of N_2-fixing BGA (C/N = 7), and * primary production is 0.5 t C/ha per crop.
Azolla	20-150 kg N/ha per crop (experimental plots) 10-50 kg N/ha per crop (field trials)	224 kg N/ha per crop * One Azolla standing crop is 140 kg N/ha, and * two Azolla crops are grown per rice crop, * Ndfa is 80%.
Legume green manures	20-260 kg N/ha per crop	260 kg N/ha in 55 days * *Sesbania rostrata* is used as a green manure, * 290 kg N/ha is accumulated in 50-60 days, * Ndfa is 90%.

FIGURE 1

Inorganic N dynamics in lowland rice soils as affected by soil aeration status (from Buresh and De Datta, 1991)



Endogenous BNF system

The use of green manure to increase soil fertility and the productivity of rice has been recognized from early times in China, India, Japan and Viet Nam (De Datta and Buresh, 1989). The several types of green manures, which have been used in the Asian farming systems, vary in their effect on rice yields. Among the green manures, attention is now focused on a stem-nodulating, fast-growing, high N_2-fixing legume *Sesbania rostrata* (Ladha *et al.*, 1988) and *Aeschynomene afraspera* (Becker *et al.*, 1990).

Green manure can increase soil N content and significantly increase available P content in the soil, maintain and renew soil organic matter, and improve soil structure and physical characteristics (Jiao, 1983). According to Ladha *et al.* (1992), *S. rostrata* is probably the fastest N_2-fixing plant known with 100-285 kg N/ha fixed in 45-55 days.

Recently, there have been some exciting developments in inducing characteristics of legumes on cereals (Ladha *et al.*, 1992) . Bennett and Ladha (1992) highlighted the need for a self-sustaining rice crop and provided a critical assessment of the feasibility of nodulation and N fixation in rice.

Nitrogen utilization efficiency in rice genotypes

Genetic selection and plant breeding techniques have long been effectively used for development of disease and insect resistance in rice and, more recently, for tolerance to adverse environmental conditions such as drought, zinc deficiency, iron toxicity and salinity. However, these techniques have not been applied specifically with the objective of improving N utilization by rice. Recent research (Broadbent *et al.*, 1987) suggests that there is considerable potential for exploiting genotypic differences in N utilization efficiency by rice. Research identified traits associated with rice genotypes that support maximum grain production with a minimum input of fertilizer. The consistency of performance of outstanding genotypes demonstrates that the methodology developed by Broadbent *et al.* (1987) is feasible and practical for continued research on genetic improvement of N utilization efficiency in lowland rice. Further methodology development studies by De Datta and Broadbent (1988) demonstrated that the growth duration of genotypes was a factor in the differences among genotypes. Most of the high ranking genotypes for N utilization efficiency were of medium or long duration. It is now possible that advanced breeding lines can routinely be screened for their N utilization efficiency, a valuable trait in rice for resource-poor farmers. The ranking of genotypes according to one, two, five or nine parameters is presented in Table 2.

In a subsequent study by De Datta and Broadbent (1993) factors associated with the development of rices known to differ in N-use efficiency were examined. Patterns and rates of N uptake were similar among duration groups up to the harvest of short-duration lines. The longer period for N accumulation available to long-duration rices did not enhance values, although six of the most N-efficient lines were medium duration and four were long duration. Translocation of nitrogenous compounds and other dry matter from leaf to spikelets as reflected by the ratio (leaf weight/dry matter) and loss of leaf N between panicle initiation and harvest as a product of maximum leaf N were also well correlated with N-use efficiency.

Fertilizer nitrogen management

The most widely used plant nutrient is N, and because of its advantages in production and savings in shipping and distribution costs, urea is the principal dry N source for rice. However,

TABLE 2

Rankings of genotypes according to one, two, five or nine parameters*
(adapted from De Datta and Broadbent, 1988).

Genotype	Non-fertilized						Fertilized							
	Three dry seasons			Three wet seasons			Three dry seasons				Three wet seasons			
	Number of parameters													
	1	2	5	1	2	5	1	2	5	9	1	2	5	9
100-109 d maturity														
IR8455-78-1-3-3	12	12	12	11	11	11	11	12	12	12	12	12	12	11
110-119 d maturity														
IR21912-56-3-1-2-2	2	2	2	1	3	2	1	1	2	3	2	1	2	5
120+ d maturity														
IR15323-78-1-3-1	1	1	1	4	5	6	2	2	1	1	5	3	6	4
IR42 (control)	5	7	7	6	6	7	6	7	4	2	4	2	3	3

* 1 = Y; 2 = Y and WP/N_t; 5 = Y, Y/N_t, WP, WP/N_t, and DM/N_t; 9 = Y, Y/N_t, WP, WP/N_t, DM/N_t, WP/N_f, WP/N_s, DM/N_f, and DM/N_s.

field studies have shown that most N fertilizers are highly susceptible to different types of loss (De Datta and Buresh, 1989). Urea is the least efficient type of the NH_4^+ containing or NH_4^+ producing N source. Various reasons have been given for the poor efficiency of nitrogenous fertilizers, including loss of fertilizer N by leaching, runoff or emission of N_2 and/or NH_3 into the atmosphere (Savant and De Datta, 1982).

In most lowland rice-growing areas, the leaching of N is not a problem. Rice is primarily grown on heavy clay soils, or sandy soils overlying impervious clay horizons, or on soils puddled to reduce water flow into subsurface horizons. In general, however, it appears that the main cause of fertilizer inefficiency in lowland rice is gaseous emission of dinitrogen and/or ammonia to the atmosphere. Very little N is lost as nitrous oxide, nitric oxide or nitrogen dioxide (Simpson and Freeney, 1988).

Nitrogen (^{15}N-labelled) balance studies in rice

Nitrogen balance studies using ^{15}N labelled fertilizer have shown that losses were greatest when fertilizer was applied directly into the floodwater and least when the fertilizer was either deep-placed or incorporated into the soil (De Datta *et al.*, 1987). Results suggest that NH_3 volatilization was the most important pathway for N loss (Fillery and De Datta, 1986; Fillery *et al.*, 1986). Subsequent studies using the bulk aerodynamic method for determining NH_3 loss from plots were assessed at one site in the Philippines before being used in conjunction with the ^{15}N balance method to evaluate the effectiveness of a number of management practices for reducing gaseous loss of NH_3 and dinitrogen. Fertilizer N recovery by the rice plants was significantly increased by incorporating N in puddled soil without surface water (De Datta *et al.*, 1989).

In the past 10-15 years, several ^{15}N balance studies were conducted to assess ^{15}N loss from lowland rice soil systems where ^{15}N recovery in plants and in soils were added to obtain the total ^{15}N recovery and ^{15}N unaccounted for was assumed as ^{15}N loss (De Datta, 1987). It is now widely appreciated that extensive N loss which accompanies poor fertilizer management is the major cause of poor N recovery. The highest N losses occur from broadcast urea into the floodwater during the early plant growth stages. Fillery and De Datta (1986) and Fillery *et al.* (1986) found 41-60% loss of ^{15}N-labelled urea and ammonium sulphate broadcast in floodwaters 2-6 weeks after transplanting, a practice widely followed by many tropical Asian rice farmers.

Fertilizer N remaining in the soil is generally present in the top 15 cm. Even in the most permeable soil, 17-20% of the supplied ^{15}N was recovered in the 0-15 cm layer and less than 4% from the 15-30 cm depth (Katyal *et al.*, 1985). Negligible quantities of ^{15}N were found below 30 cm of soil depth at the end of the growing season. Most of the fertilizer ^{15}N (>98%) remaining in the soil was incorporated into the organic pool at harvest (Crasswell *et al.*, 1985).

Plant recoveries of fertilizer N by the crop at harvest vary from 17 to 54%. Low plant recoveries are generally associated with the loss of applied N. But in other cases (Vlek and Byrnes, 1986), inefficiency in N recovery was due to immobilization or biological interchange (Jansson and Persson, 1982). Westcott and Mikkelsen (1987) found a 15-35% soil recovery of ^{15}N labelled milk vetch. Nitrogen losses from ammonium sulphate on milk vetch were similar at lower applied N levels.

In a recent study at IRRI by Dekamedhi (1991), prilled urea was compared with green manure to develop ^{15}N balance in soil plant systems (N budget). Results suggest that prilled urea gained significantly higher ^{15}N recovery in plants than did green manure. At 30 days after planting (transplanting or broadcasting) ^{15}N recovery was higher with prilled urea than with green manure. ^{15}N loss data represent the ^{15}N not accounted for in the aboveground plant parts and those which remained in the soil plant roots (Figure 2).

At harvest, green manure gave 71-73% N recovery, while prilled urea gave 64-65%. Unaccounted for ^{15}N was between 35-36% with prilled urea and 27-29% with green manure. ^{15}N retained in the soil with green manure was always significantly higher than that of prilled urea, both at 30 days after planting and at harvest.

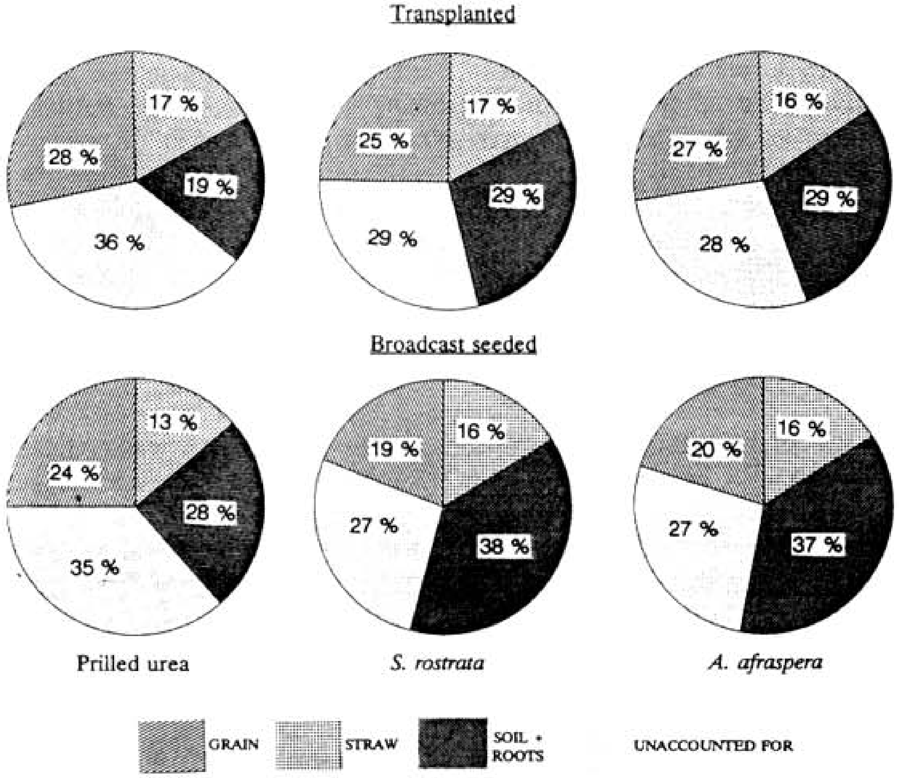
In another study, also at IRRI, Diekmann *et al.* (1993) studied recoveries of N from green manure and inorganic fertilizer sources, using ^{15}N labelled materials. Their results suggest that ^{15}N recoveries averaged 90% for green manure (*S. rostrata* and *A. afraspera*) and 65% for urea treatments. High partial pressures of NH_3 in the floodwater and a high pH probably resulted from urea applications favoured losses of N from the urea treatment. Results suggest that green manure can supply a substantial proportion of the N requirements of lowland rice. N released from *S. rostrata* and *A. afraspora* green manure was in synchrony with the demand of the rice plant. Green manure reduced the N losses from ^{15}N labelled urea, possibly due to a reduction in the pH of the floodwater. Positive added N interactions (ANIs) were also observed. At harvest an average of 45% of applied N remained in the soil for green manure and 25% of N remained for urea.

PHOSPHORUS

Phosphorus deficiency occurs in millions of hectares of Ultisols, Oxisols, Vertisols and certain Inceptisols, particularly in Andepts and acid soils. These soils are not only low in available P but they also fix P fertilizer into a highly insoluble form. Response to P occurs also in millions of hectares of the world's rice land (De Datta, 1981; Greenland and De Datta, 1985).

FIGURE 2

^{15}N balance of applied green manure and urea in transplanted and broadcast seeded IR72 flooded rice at harvest, IIR, 1990 dry season. N rate = 90 kg/ha (from Dekamedhi, 1991)



The low rice yields in these P deficient soils are probably due to the soil's low fertility, particularly their low plant-available P. For modern high-yielding rice varieties, adequate P nutrition is essential because modern varieties take up about three times more of the nutrients from the soil than do traditional varieties.

Considerable research has been conducted for alternative means of supplying P for crop production in tropical soils. Research has focused on the use of low-cost indigenous material such as locally available phosphate rock deposits, farmyard manure, or plant residues. Many studies have indicated locally available ground phosphate rock was often found inferior to that of other P sources that are commercially available. Evidence has been gathered on the agronomic effectiveness of partially acidulated phosphate rock over single superphosphate or triple superphosphate that revealed the practicability of using acidulated rock phosphate to provide the phosphorous requirement for rice in acid soils.

A procedure has been developed to allow for a choice of P sources on the basis of both agronomic effectiveness and the prices of P in TSP and of phosphate rocks (De Datta, 1983).

Dipping rice seedlings into a P fertilizer slurry before transplanting has also been reported to be useful. In China, this practice has resulted in a 40-60% saving on P fertilizer in irrigated rice (Ru-Kun *et al.*, 1982). The same authors also suggest that for rice, the best time and method of P fertilization appears to be the application of the total amount of a basal dose at transplanting for the following reasons:

- more P is required by the rice plant during the early growth stages;
- increased available P after flooding the soil falls short of the P requirement at the early stage;
- sufficient P supply encourages the development of a root system and tillering;
- in areas of low temperature, more P is required in the early stages of rice growth;
- P application at transplanting is more convenient than topdressing later.

Phosphorus application in rice-based cropping systems

The variation of soil P under the rotation of rice and upland crops influences the direct as well as the residual effects of P fertilizer (Bradley *et al.*, 1984; Willet, 1989). Generally, fertilizer P recovery by rice seedlings ranges from 8 to 20% (Ru-Kun *et al.*, 1982), with 80-90% of the applied P remaining in the soil for the seedling crop. As P availability changes with alternate drying and wetting (or submerging), the P applied to the upland crop may have a greater residual effect on the preceding crop, whereas P applied to the rice may have less residual value for the preceding upland crop (Ru-Kun *et al.*, 1982). Bradley *et al.* (1984) suggested that fertilizer P should be applied when waterlogging is least likely to occur to maximize P fixation before being used by the plant. In a study using eight lowland rice soils of contrasting properties, Ru-Kun *et al.*, (1982) reported that the total P uptake by crops and the total yield of wheat and rice grown in rotation doubled when all P was applied to the upland wheat crop as compared to when all of the P was applied to lowland rice.

In another study, Willet and Higgins (1980) reported that the depressing effects of a lowland rice crop on subsequent upland crop growth may have declined by the third year after drainage of the rice crop. Phosphorus absorbency, and corresponding increase in P-availability, would be expected during the two years after drainage of the rice crop. This could be important in the management of soils underlying rice-upland crop rotation, and for the efficient use of P fertilizer (Sanyal and De Datta, 1991).

Recycling of fertilizer P through a preceding green manure crop may also be beneficial for the succeeding lowland rice crop. Singhabutra *et al.* (1987) observed that green manuring with *Sesbania* spp. in the light textured soils of Thailand significantly improved the soil-P status, and also significantly increased rice yield. Beri and Meelu (1980) found that applying P to the green manure crop was beneficial to N accumulation, and increased rice yield (on a soil low in available P) more than did P applied directly to rice.

Ru-Kun *et al.* (1982) also reported that phosphate rock applied to a radish crop preceding rice led to a substantial yield increase of the transplanted rice. Radish is produced in some parts of China as a green manure crop.

Phosphorus applied to a green manure crop was found to be more beneficial to the rice crop than when it was applied directly to the following rice crop (Ru-Kun *et al.*, 1982). Similarly, in extremely infertile acid soils such as are found in most of northeastern Thailand, applying farmyard manure, a traditional farmers' practice in the region, or P fertilizer was thought to improve significantly the biomass and N accumulations of the previous *S. rostrata* crop. This approach enhanced the availability of nutrients to that rice crop more favourably than when materials were applied directly to the rice crop (Herrera *et al.*, 1989). Subsequent studies by Medhi (1991) suggest that the less water-soluble and the less expensive phosphate rock or partially acidulated phosphate rock were as effective as the more soluble, but more expensive, triple superphosphate in lowland rice. Application of phosphate rock to *S. rostrata* has a marked ability to convert P from phosphate rock into an available form. Thus, applications of phosphate rock to a preceding *S. rostrata* crop offer potential for rice to gather more P than applications of phosphate rock to the rice crop itself. Research further suggests that both Olsen and Pi tests are the best methods of determining P for the growth and yield of rice.

From the results of experiments at nine sites in five countries in south and southeast Asia, De Datta and Gomez (1982) suggested that rice responses to P and K should be evaluated with N, and in continuous rice cropping in several seasons. Large interaction effects between P and N and between K and N were observed.

POTASSIUM

Intensive cropping and higher potassium removal from the soil necessitate increased use of K-containing fertilizers. The amount of exchangeable K in the soil directly available to plants is related to the clay content and to the intensity of mineral decomposition of soils rich in illite and montmorillonite. A portion of the non-exchangeable K also may be available to plants. Illite type clay minerals are, however, not common in soils of the humid tropics.

The pattern of K uptake follows most closely that of vegetative growth. Seventy five percent of the total K requirement is taken up even before the booting stage, and most of the remaining K even before grain formation begins. Potassium content is highest in leaves and culms, with relatively little K accumulated in the milled grain. There is little K translocation among plant parts (De Datta, 1981).

Available K in the soil varies widely. It may range from a few kilogrammes per hectare of furrow depth to 25 mg/kg or more in soils formed from fine-textured sedimentary materials. Because many lowland rice soils occur in river basins or alluvial valleys and are relatively youthful soils, their K content is frequently high. Where traditional agriculture has shifted to maximum yield concepts, a significant transition to the use of balanced nutrients such as NP, NK, and NPK fertilization of rice, with good economic returns, has occurred (De Datta and Mikkelsen, 1985).

In Korea, Japan, and China, when rice yields are high (4.5 to 7.0 t/ha), balanced fertilizer use (NPK and sometimes Si) is emphasized. In other south and southeast Asian countries, where national average yields vary from 2-3 t/ha, only N fertilizers are generally recommended. Phosphorus or potassium are applied only to deficient soils in these countries.

Results from China (Xie *et al.*, 1981) demonstrate that K response is markedly increased with increased K levels.

Integrated nutrient management and balanced fertilization

The K requirement of rice is somehow supplied by plant residues, mulch or stubble, straw incorporation and K in irrigation water. In countries such as China and India, where organic manures are extensively used, response to K from chemical fertilizers correspondingly decrease.

Green manuring can be valuable for the P and K, as well as the N, nutrition of rice, where inorganic fertilizer costs are higher, land with marginal use is abundant and costs for harvesting, transporting, spreading and incorporating green manure material are inexpensive (De Datta and Morris, 1984).

Maintaining high yields requires fairly close adherence to the optimum balance in nutrient concentration. There are contradictory reports on K and Zn interactions. There seems to be some evidence that a definite interrelationship exists among K, Ca and Mg concentrations in the different rice plant parts, hence interaction responses occur of the nutrients deficient in the soil.

SULPHUR

Sulphur occurs in the soil in both organic and inorganic forms, with organically bound forms providing the major source. In peat soils (Histosols) the organic fraction can be almost 100% of the total S present. C/N and N/S ratios tend to decrease with soil depth.

The inorganic forms of soil S are mainly SO_4^{2-}. Upland soils may accumulate high concentrations of $CaSO_4$, $MgSO_4$ and Na_2SO_4 whereas in the lowlands, SO_4^{2-} is present either in solution form or is adsorbed on soil colloids. Ammonium sulphate (24% S) and single superphosphate (14% S) are the common inorganic S sources. However, gypsum and elemental S are similarly as effective as ammonium sulphate, possibly because of the concentration of elemental S in sulphate through oxidation in the root rhizosphere.

Sulphur concentrations vary with plant part and age, averaging 0.25% during the early vegetative phase and 0.10% at maturity. However, the rice grain contains higher S levels than does the straw. Yoshida and Chaudhry (1972) established plant critical levels based on two criteria – DC_{50} was set as the S content required in plant tissues for 50% of the maximum yield, whereas DC_{100} was that required for total maximum yield. However, the generally accepted principle is the level required for the production of 95% of the maximum yield. Islam and Ponnamperuma (1982) established critical total S levels for specific rice plant parts at specific growth stages: 0.11% for the shoot at maximum tillering, 0.055% in the straw at maturity and 0.065% in the grains. In flooded (lowland) rice, S levels in the straw of S-deficient plants range from 570 to 620 ppm, whereas those of normal plants range between 1270 and 1330 ppm.

Rice responses to sulphur

Rice responses to S have been reported from many countries. Continued use of modern varieties with intensive cropping practices can remove 10-13 kg S/ha per crop and result in increased S response in many lowland rice soils (De Datta, 1981). Sulphur response in the field ranged from 34 to 120% (Wang *et al.*, 1976).

Sulphur deficiency and response to S are widespread in Indonesia and Bangladesh (Blair and Till, 1983). In Punjab, India where a rice-wheat rotation has resulted in increased cereal production, S deficiency and S response have become widespread. Similar high response to S application has been recorded in Indonesia (Ismunadji *et al.*, 1975). Mamaril *et al.* (1976) reported that yields in farmers' fields in South Sulawesi, Indonesia, were 12-45% higher than those in control, with application rates of approximately 100 kg S/ha.

In Bangladesh, where sulphur deficiency has been recorded in sizable rice growing areas, yield increases of 0.3 to 2.2 t/ha were observed in farmers fields with sulphur application (Hoque and Hobbs, 1980). In one study, the grain yield increases of rice were 72% with ammonium sulphate and 43% with magnesium sulphate.

ZINC

Zinc is considered the third most important nutrient in lowland rice after N and P. In the soil, the element occurs in exchange sites of clay minerals and organic matter or is adsorbed on soil surfaces. Mandal and Mandal (1986) presented a path coefficient analysis which revealed that organic complexed Zn plays the most important role in Zn nutrition in lowland rice. Critical plant Zn level is estimated to be at or below which the plant shows deficiency symptoms or gives a significant response to applied Zn. Forno *et al.* (1975) set the critical levels of Zn in deficient rice plants to be about 15 ppm. Critical Zn levels have also been established for various plant parts at specified growth stages. Generally, 20 ppm is considered the level of plant Zn below which deficiency symptoms start to appear (Yoshida *et al.*, 1973).

Visual symptoms of Zn deficiency generally appear 2-3 weeks after planting and in rice are characterized by chlorotic midribs, reddish brown discolorations of the lower leaves, stunted growth and reduced tillering (De Datta, 1981). If the deficiency becomes acute, the leaf angle increases making the plant umbrella-like. Zinc deficiency occurs on Histosols, sodic, calcareous and sandy soils that have been wet for prolonged periods.

Zinc deficiency in rice

Incidence of Zn deficiency appears more closely related to zinc availability than to zinc content in the soil, and spontaneous recognition of affected crops is common.

The incidence of zinc deficiency has increased recently because of the replacement of traditional rice varieties by modern varieties which are less tolerant to zinc deficiency, removal of large amounts of zinc by modern varieties, replacement of ammonium sulphate with urea, increased use of phosphate fertilizers and double or triple-cropping of irrigated rice fields (De Datta, 1981).

Varieties with tolerance to zinc deficiency would reduce the problem of growing rice in zinc-deficient soils. On organic and calcareous soils, it is advisable to use a combination of varieties tolerant to zinc deficiency and transplant with a 2% zinc oxide dip (Orticio and Ponnamperuma, 1977). Abilay and De Datta, (1978) obtained a yield of 4.9 t/ha in rice with 20 kg Zn/ha treatment, where as no zinc treatment gave zero yield on a calcareous soil in the Philippines.

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Use of organic materials and mineral fertilizers in an integrated nutrient system in French farming

The subject of this presentation forms part of the wider concept of 'sustainable agricultural development', a subject which brings together many people in a large number of meetings. To clarify the subject, the following definition is proposed:

It is based on evolving processes for agricultural production and maintenance of the countryside which:

- permit the rural population to live and survive,
- satisfy society's demands as regards food, production and leisure,
- do not harm the environment, and protect the natural resources, soil, water and the atmosphere.

This definition is in line with the one proposed by Professor P.B Tinker, of the University of Oxford, in a conference on 'The demand for Sustainability' presented in Cambridge on 8 December 1993.

Sustainable development is one that:

- is economically sustainable; it must produce an economic reward for those undertaking it (which may well include subsidies in various forms);
- must not damage the resource base on which it rests; if it does, it will sooner or later become impractical or uneconomic. 'Resources' in this context must include replacements or alternatives to presently used materials;
- must be socially and ethically acceptable to the population at large, at the scale of either a small region (for a new road), a whole country (for a change in agricultural regulations) or the whole world (for a conservation issue such as whale hunting).

PAPER 5.2

J.C. Ignazi, Chairman of COMIFER (Comité français d'étude et de développement de la fertilisation raisonnée), Paris, France

Consequently:

- agriculture is tending towards diversification, with several agricultural 'systems' (monoculture, polyculture, livestock, horticulture, etc.) seeking the best possible adaptation to soil and climatic conditions, but which are also economic and socio-culturally viable;
- conventional 'productivity' agriculture no longer dominates; certain types of less intensive agriculture are emerging;
- it is necessary to use available land more effectively, to make better use of local resources, in particular of organic materials.

These trends lead to the concept of an integrated approach to production techniques and agricultural activities, where integrated means:

- that all the proposed techniques are optimal, from the point of view of sustainability, and particularly with regard to crop nutrition;
- that an attempt is made to make use of interactions between the different factors of production.

RATIONAL FERTILIZATION IN FRANCE

A case study of an integrated system of plant nutrition was carried out. It addressed the challenge to consider an agricultural activity which is diverse and profitable, compatible in the long term with the quality of the environment (soil, water, atmosphere). The agricultural community and the public authorities decided together to accept this challenge.

Concept of rational fertilization

This concept has been defined and developed for over ten years by agronomists and scientists of the COMIFER group: researchers in official organizations, agronomists and development staff of advisory networks of agricultural organizations, and also by the industry and distribution organizations (cooperatives and private merchants), who formed working groups and who organized their work in common.

A recent Congress, organized in November 1993[1], examined in particular the possibility of the rational utilization of organic materials in present agricultural systems. On this occasion, it was recalled that rational fertilization is a set of agricultural and practical rules, organized according to a coherent logic both from the point of view of the farmer (who acts) and the agronomist (who advises). This set of rules allows the farmers to make a clear choice as regards the fertilizer materials which they consider necessary to achieve quantitative and qualitative production objectives in the context of their cropping systems, the potential of their soil and climatic conditions and of the many constraints to which they are subject, concurrently conserving, even improving, the ecological characteristics of the environment in which they operate.

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[1] "Matières organiques et agriculture", 5th day of "La fertilisation raisonnée", Blois, 16-18 November 1993.

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7. All other measures used to produce these crops must be optimized, in order to obtain maximum efficiency of the rooting system: the correct choice of variety, appropriate cultivation and plant protection measures.

8. Consideration should be given to **placement** in the soil profile by incorporation or, with surface application, to **split applications**, especially for nitrogen, in order to correspond to the periods of physiological requirements. The physical quality of the products should also be taken into account, in order to optimize the spreading techniques according to the materials available.

Some 'key points' emerge from the above considerations:

- The **input/output balance** of nutrients on each plot should be sought, in order to avoid **deficits**, which risk in due course to reduce the fertility of the soil, or surpluses which, especially in the case of nitrogen, increase the risks of losses of nitrates to water or through atmospheric emissions.

  It is the search for this balance, for each plot, and for each vegetative cycle, that should be ensured. Computer programs have been developed by advisers and even by farmers, such as the programs A290BIL or TOP'A2.

- **Mineralizable organic sources** of nutrients during the season should be taken into account in the fertilization plans:

  - either the soil reserves: humus, crop residues,
  - the supplies available on the farm or those which can be brought in economically: slurries, manure, sludges, compost. Particular attention should be paid to both the precise assessment of the nutrient content of these products (according to analyses or standards), and to the quanitities effectively applied.

  As regards the by-products such as sludges or composts and organic wastes in general, it is necessary to assess their fertilization value but also the absence of undesirable substances, such as toxic or contaminating mineral or biological materials.

  These materials offer a real opportunity from a fertilization point of view, but the necessity of standardization and strict regulation is evident, so as not to entail any risk, either for human or animal health or for the biosphere.

- Finally, the importance of **coherent optimization** of all the techniques used, in order to exploit synergistic effects such as water and nutrients, pH and nutrients, soil structure and root nutrition, etc.

Action programme developed in France by CORPEN (Committee for the Prevention of Water Pollution from Agricultural Activities)

This Committee was established in 1984, jointly by the Ministry of Agriculture and the Ministry of the Environment, in order to bring together experts of all origins, with competence in the fields of agriculture and water quality, in order to prepare a technical and scientific basis for an active policy for the protection of resources (deep water tables, aquifers, surface waters). The first subject dealt with was the increase in the nitrate content of water, and it was apparent that the concept of 'rational fertilization' should be one of the key factors in any action.

The proposed programmes, supported by all the organizations concerned, especially the associations of farmers, of water authorities and public authorities, taking account of economic realities (reform of the Common Agricultural Policy), prepare the necessary regulations (application of the directive of the European Union), while integrating agro-environmental measures which have already been decided upon.

The most important recommendations of CORPEN in this respect have been:

- October 1986: 'Improvement of agricultural practices to limit nitrate losses'. This document was up-dated and republished in June 1993.
- April 1993: 'Code of best practices', in accordance with EEC Directive 91/676. This code was made official by a decree of 31 August 1993.
- June 1993: 'Action programme for plant protection products'

In this code, one finds the same key points as in the rules of rational fertilization: nutrient balances (input/output), optimum use of organic sources, to which have now been added:

- maximum soil cover (catch crop)
- control of crop residues
- soil cultivation, irrigation, drainage
- simple landscaping: hedges, grass strips.

It is clear therefore that the concept of integrated nutrition has become an important part of governmental policy, supported by the agricultural organizations, the industry, the water distributors and water authorities, the catchment area agencies, the distributors and the agro-industry.

The 'FERTIMIEUX' (better fertilization) programme: a network of concrete operations

In order to put the principles of integrated plant nutrition systems into practice, particularly in areas where the nature of the soil, climate, or systems of land use, make the protection of water resources more difficult, a network of advisory operations to **all** farmers in each zone has been established, according to instructions defined by CORPEN, and under the responsibility of the Ministry of Agriculture.

These zones correspond to catchment basins covered by well defined types of agriculture, where the causes of the degradation of the water quality have been clearly identified, particularly when due to poor agricultural practices. In general it is inappropriate fertilization which is the cause of these phenomena. Each 'Pilot Committee' thus gave priority to an improvement of fertilization recommendations.

This Committee brings together all the advisers present in the zone, and it is together that they organize the dissemination of advice to farmers.

It is should be noted that farmers and public authorities cooperated and worked together in these operations, the impact of which is beginning to be recognized, especially by public opinion. The first recorded results lead one to believe that, thanks to the application of the principles of rational fertilization, and the 'best practices', it is possible to continue to cultivate in a reasonable manner, profitably, while at the same time protecting, even improving, water quality.

CONCLUSION

In order to be efficient, and thus to become adopted, an integrated system of plant nutrition must:

- be perfectly adapted to the requirements and constraints of cropping systems applied by the farmers, in accordance with their diversity of soil and climate, but taking account of present and future economic conditions, and also the socio-cultural aspects;
- optimize the use of local resources, obviously mineral fertilizer, liming materials etc., but also organic materials, from all origins, taking careful account of their characteristics;
- limit externally purchased inputs to what is strictly necessary, whereby the production cost will be reduced, the environment will be preserved, and the quality of the crops and the income of the farming families will be maintained or increased.

Combined use of inorganic and organic plant nutrients in a West European arable farming system

In West European agriculture inorganic fertilizers are extensively used because they are cheap, easy to handle and have a rather predictable effectiveness. Extensive use of inorganic fertilizers may not only result in high crop yields, but also in environmental pollution (Neeteson, 1994). Nutrients can also be supplied to crops through organic fertilizers, such as animal manures, composts and green manures. Most organic fertilizers are produced as agricultural by-products and their recycling thus does not constitute an additional import of nutrients into agriculture. They are used as slow-release fertilizers and as soil quality improvers on account of their high organic matter content. However, their effectiveness as a source of nutrients for crops is less predictable than that of inorganic fertilizers. Ideally, from the point of view of sustainability, organic fertilizers should be used as much as possible whereas additional inputs of nutrients to agricultural ecosystems in the form of inorganic fertilizers should be restricted as much as possible.

In the autumn of 1985 the Dutch Programme on Soil Ecology of Arable Farming Systems was initiated to test the hypothesis that appropriate changes in farm management open the way to alter the structure and functioning of agro-ecosystems toward a better nutrient use efficiency, sustained improvement of soil structure, and effective pest, disease and weed control (Brussaard *et al.*, 1988). Changes in farm management included reduced nutrient inputs through the combined use of inorganic and organic fertilizers, reduced use of biocides and reduced soil tillage.

In this paper some of the many results obtained in the framework of the above-mentioned Programme are summarized. The results presented here only concern the effects of the combined use of inorganic and organic fertilizers on crop yields and on the nitrogen budget. The data are extracted from Lebbink *et al.* (1994) and Van Faassen and Lebbink (1990, 1994). Results concerning the effects of reduced use of biocides and reduced soil tillage, as well as the effects of the treatments on soil fauna and soil physics are described in special issues of Geoderma (1993, volume 56) and Agriculture, Ecosystems and Environment (1994).

PAPER 5.3

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EXPERIMENT

To test the hypothesis that the combined use of inorganic and organic nitrogen fertilizers together with a reduced use of biocides and soil tillage could improve the sustainability of arable farming systems, a long-term field experiment was conducted in Marknesse, The Netherlands, at the experimental farm "Dr. H.J. Lovinkhoeve" of the DLO Research Institute for Agrobiology and Soil Fertility (AB-DLO). The soil is a calcareous silt loam classified as a Typic Fluvaquent. Soil pH-KCl is 7.5, total N content 0.10-0.14%, $CaCO_3$ content 9%, and the sand, silt and clay contents are 12, 68 and 20%, respectively. The soil was reclaimed from a large fresh water lake in 1942. Annual rainfall between 1943 and 1990 averaged 740 mm. The experiment started in 1985 on plots of a previous experiment with a low (average 3200 kg/ha/year) or a high (average 5650 kg/ha/year) input of organic matter since 1966. In the low organic matter treatment the organic matter input occurred only through crop residues which remained on the field. In the other treatment, in addition to crop residues remaining on the field, farmyard manure was also applied and green manures (leys) were included in the rotation. Plot size was 96 m x 85 m. At the end of the previous trial the organic matter content of the 0-25 cm soil layer was 2.25 and 2.75% on the low and on the high organic matter input treatment, respectively (Van Faassen and Lebbink, 1990). In the autumn of 1985 the plots were divided into two equal parts (48 m x 85 m). On one part conventional crop management was practised and on the other integrated crop management until 1992. Integrated crop management included a reduced use of inorganic nitrogen fertilizers together with an increased use of organic fertilizers. The organic fertilizers applied in the integrated management treatment were mushroom compost (30 t/ha after harvest of the winter wheat crop, containing 20% organic matter and 0.7% organic N) and dehydrated pelleted animal manure (3 t/ha before planting of the potatoes, containing 50% organic matter and 2% organic N). Integrated crop management also included reduced use of crop protection agents and reduced soil tillage (Table 1).

Each part of the plots consisted of four subplots of 12 m x 85 m to be able to grow the four crops of the four-year rotation simultaneously. The rotation was winter wheat (*Triticum aestivum* L.) - sugar beet (*Beta vulgaris* L.) - spring barley (*Hordeum vulgare* L.) followed by undersown ryegrass (*Lolium perenne* L.) - potatoes (*Solanum tuberosum* L.). Conventional and integrated crop management was thus practised during six consecutive years on fields with a high or a low soil organic matter status in such a way that each year all four crops of the rotation were present.

Further details about the setup of the trial and, for example, sampling procedures are described elsewhere (Lebbink *et al.*, 1994). The results presented in this paper refer to the period 1988-1991.

INTEGRATED CROP MANAGEMENT AS COMPARED WITH CONVENTIONAL CROP MANAGEMENT

Crop yields and nitrogen uptake

Crop yields obtained in the integrated management system were 3-16% lower than in the conventional system (Table 2). The largest difference was found for winter wheat independently of the soil organic matter status. For potatoes, however, soil organic matter

TABLE 1
Major differences between the conventional and the integrated management systems used

Management practice	Conventional management	Integrated management
Nitrogen fertilization		
Inorganic fertilizers	According to the current recommendations	About half the amount applied at conventional*
Organic fertilizers	Crop residues	Crop residues, compost, manure
Crop protection	Conventional use of pesticides including soil fumigation	Less than conventional use of pesticides, no soil fumigation
Soil tillage	Ploughing depth 20-25 cm	Ploughing depth 12-15 cm

* At the low soil organic matter status treatment an additional amount of 30 kg N per ha was applied to compensate for the lower nitrogen mineralization.

TABLE 2
Crop yields (t/ha) during the period 1988-1991. Each crop was grown each year in the rotation winter wheat-sugar beet-spring barley + ryegrass-potatoes. The values are the averages of results obtained in the four consecutive years (after Van Faassen and Lebbink, 1994)

Crop	Low soil organic matter status		High soil organic matter status	
	Conventional	Integrated	Conventional	Integrated
Winter wheat (grain, dry matter)	6.7	5.6	6.7	5.6
Spring barley (grain, dry matter)	5.3	4.7	5.0	4.8
Sugar beet (sugar)	14.5	13.3	14.3	12.9
Potatoes (tubers, fresh weight)	57.4	50.6	60.1	58.4

status strongly influenced the yields obtained in the integrated system: at the high status yields were almost as high as in the conventional system, whereas at the low status yields were 12% lower. In the conventional system soil organic matter status did not have an effect on crop yields (Table 2).

Unfortunately, the setup of the trial does not allow conclusions on the separate effects of fertilization, biocide use and soil tillage. With one exception, i.e. for the lower yields of winter wheat in the integrated system, which is probably due to reduced crop protection, it is reasonable to assume that the yields obtained were predominantly determined by the fertilization practice. This is confirmed by the data on nitrogen uptake by the crops (Table 3). Nitrogen uptake in the integrated system was 5-22% lower than in the conventional system, with the lowest uptake when soil organic matter status was low. Nitrogen uptake in the conventional system was largely independent of the soil organic matter status.

When inorganic nitrogen fertilizer application was reduced by 50%, the results suggest that indigenous soil organic matter together with organic fertilizers can supply sufficient nutrients to achieve about 90% of the yield obtained in conventional systems.

TABLE 3

Nitrogen uptake (kgha) during the period 1988-1991. Each crop was grown each year in the rotation winter wheat-sugar beet-spring barley + ryegrass-potatoes. The values are the averages of results obtained in the four consecutive years (after Van Faassen and Lebbink, 1994)

Crop	Low soil organic matter status		High soil organic matter status	
	Conventional	Integrated	Conventional	Integrated
Winter wheat	149	120	146	122
Spring barley	109	88	112	99
Sugar beet	232	182	228	198
Potatoes	225	211	245	232
Ryegrass	150	83	150	84

TABLE 4

Nitrogen budget of a four-year rotation (winter wheat - sugar beet - spring barley + ryegrass - potatoes) with a low or a high soil organic matter status. Values are averages of the period 1988-1991. Each crop was grown each year in the rotation mentioned. Data on organic manures and atmospheric deposition refer to the total amount in the four-year period (after Van Faassen and Lebbink, 1994)

Input/ output Crop/organic material	Low soil organic matter status		High soil organic matter status	
	Conventional	Integrated	Conventional	Integrated
Input of nitrogen (N, kg/ha)				
Inorganic fertilizers				
Winter wheat	165	108	138	71
Spring barley	120	71	95	47
Sugar beet	153	89	118	70
Potatoes	274	177	244	142
Italian ryegrass	70	25	70	25
Organic fertilizers				
Compost	0	200	0	200
Manure pellets	0	60	0	60
Potato seeds	10	10	10	10
Atmospheric deposition	70	70	70	70
Total N input during the four-year rotation	862	810	745	695
Output of nitrogen (N, kg/ha)				
Crop produce				
Winter wheat	149	111	146	113
Spring barley	109	88	112	99
Sugar beet	102	84	100	80
Potatoes	215	201	234	222
Total N output during the four-year rotation	575	484	592	514
Input minus output during the four-year rotation (N, kg/ha)	287	326	153	181

Nitrogen budgets

Nitrogen budgets of a complete four-year rotation of conventional and integrated crop management are shown in Table 4. Total nitrogen input was about 850 and 750 kg N per ha per four years when soil organic matter status was low and high, respectively. The difference is to be attributed to a reduced inorganic nitrogen fertilizer input when soil organic matter status was high. This is due to higher levels of soil mineral nitrogen at the end of winter, which resulted in lower amounts recommended to be applied according to the current recommendations (Neeteson, 1990). Moreover, at the low organic matter status an additional amount of about 30 kg inorganic nitrogen per ha was applied to compensate for the expected lower rate of nitrogen mineralization.

Total nitrogen output was about 600 and 500 kg N per ha per four years in the conventional and the integrated system, respectively (Table 4). The difference between nitrogen input and output amounted to about 150-200 kg N per ha per four years at the high soil organic matter levels and to about 300 kg N per ha at the low soil organic matter levels.

The difference between nitrogen input and output can not only be attributed to losses (nitrate leaching, ammonia volatilization, denitrification), but also to accumulation of nitrogen in the soil (immobilization). Drain water and soil mineral nitrogen measurements suggest that soil nitrate leaching cannot be regarded as a severe loss of nitrogen (De Vos *et al.*, 1994). Although soil pH is high, ammonia volatilization is also unlikely to have played an important role since inorganic nitrogen fertilizer was applied as $Ca(NO_3)_2$ and the organic fertilizers contained little ammonium. There is some evidence, however, that substantial losses through denitrification could have occurred (Van Faassen and Lebbink, 1990). Soil organic matter measurements showed that from 1986 to 1991 the initial soil organic matter levels were maintained under the integrated system, but decreased by about 0.2% in the conventional system. It was also found that total nitrogen in the soil increased by about 0.015% in the integrated system and was maintained in the conventional system (Lebbink *et al.*, 1994; Whitmore and Van Noordwijk, 1994). Immobilization of nitrogen can thus be regarded as an important cause of the difference between nitrogen input and nitrogen output in the integrated system.

The results suggest that in the conventional crop management system higher losses of nitrogen occurred and that in the integrated system soil organic matter levels were maintained at the initial level. The integrated system can thus be regarded as a more sustainable system than the conventional system, provided that organic matter is brought in from outside. The latter also contributes to a more efficient use of nutrients in the total agricultural ecosystem, because wastes from animal farms are then recycled on arable farms.

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Productivity, sustainability and soil management on a catchment basis

Productivity is the ratio of output to input, measured in the same units, e.g. in money or energy terms. In plant production there has been a tendency of stressing the yield, i.e. output, measured as mass/area, more than the ratio. During the last 4-5 decades, fertilizers, pesticides and irrigation water have been profitable inputs. If plant nutrients, e.g. nitrogen, are under study, it should be considered that fertilizer is not the only source of nitrogen input. Further, sustainability, i.e. the change of productivity with time, and environmental effects should be evaluated. This paper deals with soil management on a catchment basis. The geographical scope of the paper is mainly the temperate humid, or sub-humid regions of Northwestern Europe.

The term sustainability is in many ways comparable to 'good husbandry', 'carrying capacity', or similar expressions. The philosophy of good husbandry generally was the careful use of resources. Today, environmental concerns are included. CGIAR (1989) gives the following definition:

> "Sustainability is the successful management of resources for agriculture to satisfy the changing human needs, while maintaining or enhancing the quality of the environment and conserving natural resources."

Other authors include more factors. Oram (1988), mentions the system's ability to maintain productivity when exposed to external stress or shock. Dahlberg (1993), includes ethics and equity, thereby adding the normative perspective.

PRODUCTIVITY AND SUSTAINABILITY

For a farm with a set of crops, aggregated numbers, or indices, may be used for outputs and inputs, with actual prices as weighting factors (Christensen, 1975), with the following equations:

$$P = Q/X \quad (1)$$

$$P' = Q'/X' \quad (2)$$

P = Productivity
Q = Output
X = Input

PAPER 5.4

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The primes indicate aggregated numbers for all inputs and outputs.

Sustainability is then the time derivative of the productivity

$$dP'/dt = (dQ'/dt)/(dX'/dt) \tag{3}$$

Losses of nutrients would enter the equations as cost shares for replacement of nutrients, and losses of soil particles would contain cost shares for irrigation water to replace losses of available water, as well as cost shares of fertilizers to replace lost nutrients.

The major changes in agriculture since arable farming started in the neolithicum are:

- soil cultivation, leading to increased mineralization and erosion;
- drainage, leading to increased mineralization of organic matter;
- irrigation, which might be followed by salinization;
- chemical inputs, often accompanied by nutrient contamination, or, in some cases pollution, e.g. persistent pesticides.

It may be expected that the simple calculation of an optimal point, where the marginally obtained value of output corresponds to the marginally added cost of input, does not take account of long-term costs, such as contamination or pollution of waterways. Further, a calculation of the optimal amount of nitrogen fertilizer for a cereal crop might correspond to a nitrogen dose, which might give increased lodging, leading to a delay in harvesting time, thereby increasing the costs of grain drying. Additionally, this amount might give more weeds the next year (due to the lodging), possibly stronger attacks of diseases, and finally, in a humid climate, higher leaching losses, because yields might be lower than fertilized for.

Similarly, with phosphorus, a slowly growing cadmium content in the soil would not show up in a simple annual optimalization.

Major changes in management of the land

During neolithicum arable agriculture started by sowing seeds of selected species of plants in a prepared soil - a seedbed. Soil cultivation was part of a break with a nomadic lifestyle. Cultivation provided mankind with the word culture. Ploughing and labour have been synonyms in some languages. A fenced area of land was the origin of 'garden' (probably related to the verb to guard), similar to the word 'gård', 'gard' in Nordic languages, 'Garten' in German, 'jardin' in French, and 'gorod/grad' in Russian.

Important effects of soil cultivation on the soil are the removal of vegetation cover, an increased mineralization of organic matter, and increased erosion. During a long time period of agricultural history continuously cultivated fields and permanent grassland fields lay side by side. Crop rotation had a break-through in the 18th century in England, but had already been practised in The Netherlands before that time. The long-lasting system with continuously cultivated fields and grassland fields, side by side, was gradually replaced by fields with cereals, root crops and grassland/legume ley grown in a time sequence in the same field. Drainage, which was introduced as a necessary measure to cultivate poorly drained lands, increased the aeration of the soil, and accordingly the rate of mineralization. The wetlands were gradually drained and became highly productive soils.

The development in Western agriculture since the 1940s, with a tremendous increase in chemical inputs, such as fertilizers and pesticides, and return to continuously cultivated fields, has caused great concern with regard to environmental changes, such as contamination of groundwater and surface waters with nutrients, losses of soil due to erosion, and pollution of soil and water with toxic materials, such as heavy metals, PCBs, etc.

Boundaries of the system

In agriculture the farm fence is often considered the boundary of the system under study. It is possible to develop a nutrient balance for the farm, given certain assumptions, such as quantities of nutrient losses to groundwater, soil and nutrient losses by runoff to watercourses, and gaseous losses to the atmosphere. The inputs, such as fertilizers, animal feeds and other purchased inputs, and outputs, such as plant and animal products sold from the farm, are generally measurable. The control of calculations by monitoring is very difficult, if not impossible with the farm fence as the boundary. The catchment of a few square kilometres area of a first-order waterway, such as a small agricultural stream, is a more appropriate unit for checking the losses of nutrients leaving the system by the stream, and for utilizing the capacity for natural purifying processes to limit the contamination of larger watercourses. In the low-lying areas of a catchment it is possible to utilize self-purifying processes, such as trapping of sediments and nutrients in ponds, lakes, wetlands, vegetation zones, as well as denitrification in wetlands. The effects on the environment, in this case a higher order waterway, may be monitored (see Figure 1). The effects on the atmosphere may still be difficult to include in a balance sheet, and difficult to monitor.

Self-purifying processes in catchments

Permanent vegetation zones

Permanent vegetation zones are protection measures against losses of soil and nutrients by surface runoff. This measure has been used within arable areas to protect the soil surface against runoff waters in slight depressions, and other potential surface waterways, e.g. contour bunds.It is possible to utilize vegetative filter strips as part of the protection system of river banks. The vegetation zones protect against soil erosion during heavy showers, in cold climates during snow melting periods, and generally when the cropped areas are without crop cover.

At JORDFORSK research with permanent vegetation zones or filter strips has been carried out as a measure against water erosion. In Figure 2 the experimental layout is presented (see Jenssen *et al.*, 1993). The effects on conductivity, total-P, PO_4-P, total-N, suspended matter, and loss on ignition are presented in Figure 3 from Jenssen *et al.* (1993). It is observed that removal of P, total -N, and suspended matter is rather high, while the effect on conductivity, which is a measure of the contents of highly mobile ions (e.g. water soluble ions), is considerably less. An interesting observation was that there were rather small treatment differences between grassland and deciduous forest as vegetative cover. Further investigations are needed with regard to length of filter strips, as well as the long-term effects of vegetation zones.

Small streams

The self-purifying processes acting in small streams are sedimentation, bio-accumulation, adsorption to soil particles and denitrification (Jenssen *et al.*, 1993). Investigations have shown

FIGURE 1

Boundaries of the system. If the nearest part of the surroundings (environment) are included in the system, the contamination or pollution will become a concern of the system. In the agricultural landscape, the catchment of the first order waterway is a suitable management unit for sustainable agriculture. Methods of self-purification of drainage and surface waters may become part of management.

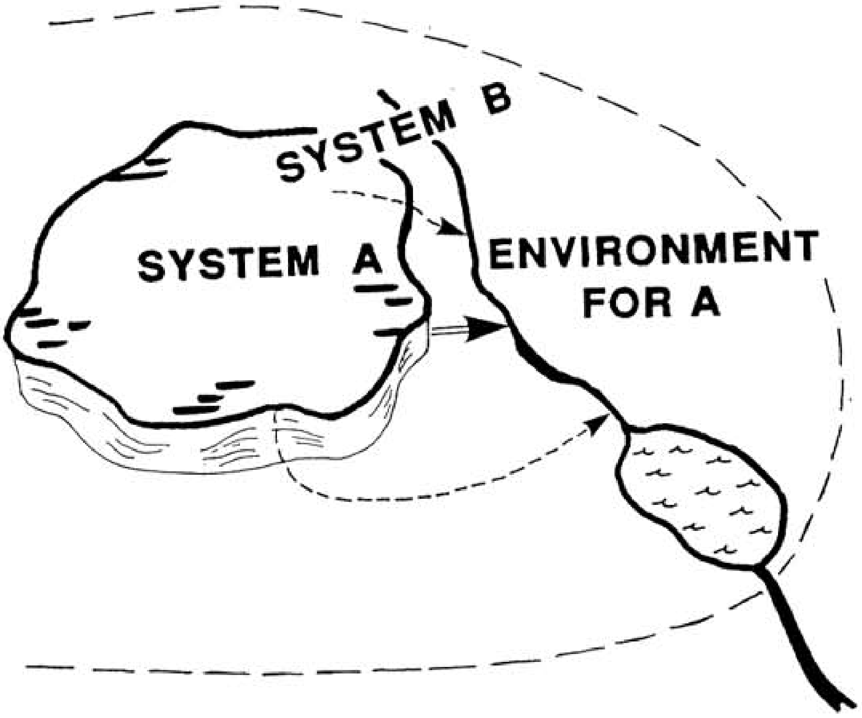


FIGURE 2

Vegetation filter strips (Jenssen *et al.*, 1993)

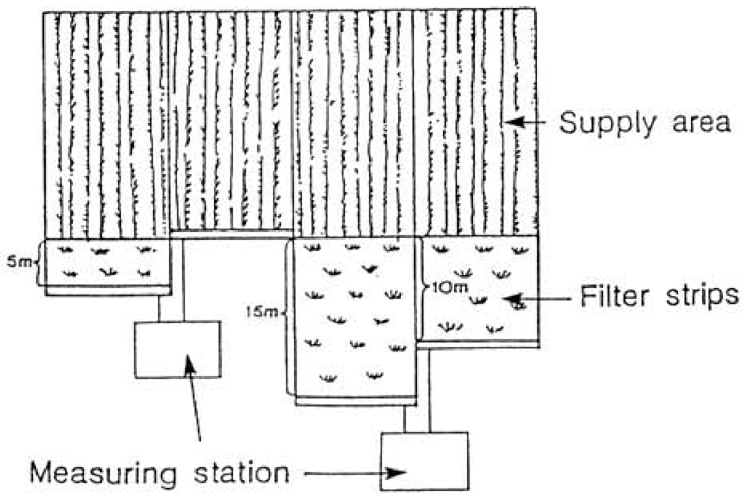
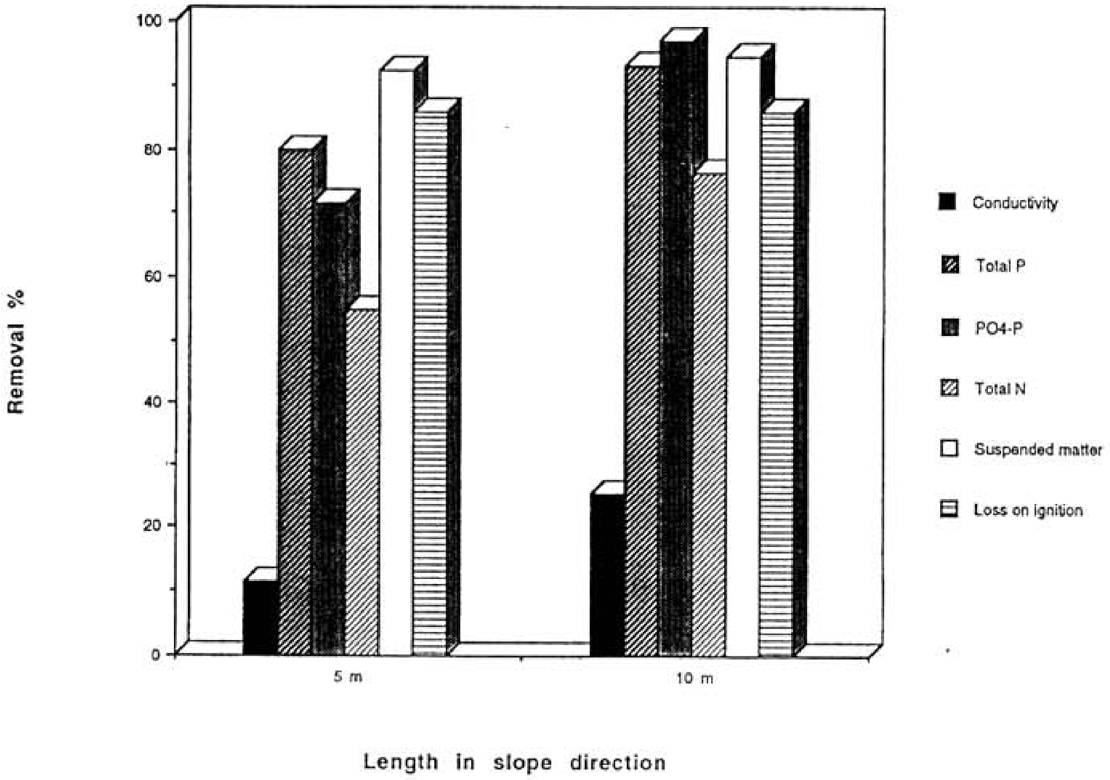


FIGURE 3
Retention in deciduous forest filter strips with 5 m and 10 m length (Jenssen *et al.*, 1993)



that restoration of original streambeds for tile-drained, closed waterways, may be a cost-effective abatement of nutrient contamination/pollution of water in first-order waterways (Fleischer *et al.*, 1989; Hammer, 1992). Sedimentation is favoured under conditions of low water velocity and a vegetated streambed. Uptake of N and P in higher water plants retains nutrients for a longer or shorter period of time. Denitrification takes place under anaerobic conditions when micro-organisms use the oxygen of the nitrate as an electron acceptor for oxidizing organic matter. The denitrification in nutrient rich streams mainly occurs in the upper 1-2 mm of the sediment, or in the biofilm established on the surfaces of plants (Nielsen *et al.*, 1989). Roseth and Faafeng (1991) showed that the N loss rate from denitrification increased with initial nitrate concentration for a temperature range of 8-16°C (see Figure 4). There are other processes operating in addition to denitrification, such as uptake of nutrients in plants and sedimentation of organic matter.

Wetlands, natural and constructed

Natural wetlands include marshes, swamps, fens and coastal marshes. Constructed wetlands may be built either as overland flow systems or subsurface systems (root zone systems) see Jenssen *et al.* (1993). A number of contaminants and pollutants may be retained or removed by a variety of microbial, chemical and physical processes. Overland flow wetlands are possible

FIGURE 4
N loss rates (mg N m^{-2}day^{-1}) in Vastadbekken at different initial nitrate concentrations (Roseth and Faafeng, 1991)

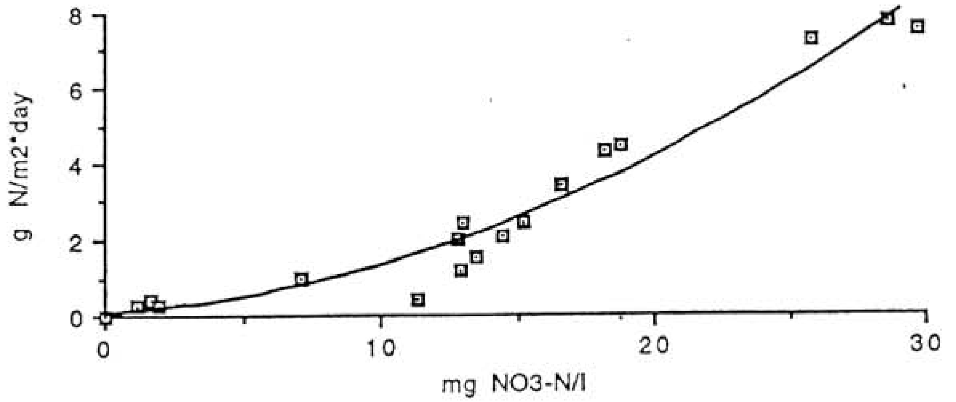


FIGURE 5
Longitudinal view of dam in Halden Basin (Braskerud, 1993)

Sediment removal	10 - 56 %
P - retention	20 - 40 %
N - retention	5 - 13 %

self-purifying measures in first-order streams receiving non-point, or diffuse additions of nutrients from their catchments. At JORDFORSK four first-order streams with catchments of 50-100 ha were dammed in 1990. Artificial, shallow lakes were dug by widening the streambed to 3.5-8.5 m, over a length of 75-100 m (see Figure 5). At the inlet the depth was about 1.5 m, while the remainder was about 0.5 m deep. Natural vegetation from nearby wetlands was planted. An investigation carried out in 1992 showed 10-56% retention of soil particles, 23-40% retention of P, and 5-13% of N, calculated from total inputs (Braskerud, 1993). In Table 1 the cost efficiency of selected measures to remove N and P from surface waters is presented.

Treatment of wastewater

A system for treatment of domestic wastewater in subsurface soil layers is a special constructed wetland (Jenssen *et al.* 1993). A large system for wastewater infiltration in soil has been tried at Setermoen at 69°N, where the annual air temperature is +1°C. Raw sewage from 5000 person equivalents has been added to two alternating sedimentation ponds of 600 m^2. The water flows by gravity from the sedimentation ponds to three infiltration basins of 2000 m^2 each. The depth of the unsaturated glaciofluvial sand and gravel below the basins is approximately 7 m. Groundwater samples from the first four years of operation showed average removals of 90, 99 and 73% for COD, P and N, respectively in the soil, according to Jenssen (1992), who mentions that the remarkably high removal of N is probably due to denitrification.

TABLE 1
Cost efficiency in US dollars per kg nutrient removed (Bratlie *et al.*, 1991)

Measure	N	P
No tillage in autumn		
- highly erodible soil	41	75
- little erodible soil	260	530
Landscaping in clay ravines	57	105
New sewage treatment plant	77	100
Construction of overland flow wetlands*		
- Halden Basin	9	60
- Trugstad, Nannestad		6

* Preliminary calculations at JORDFORSK.

The catchment as a management unit

To manage both the productivity of the land and the contaminants in the water phase, a practical management unit is the catchment of a first-order stream. Within a catchment it is possible to calculate balance sheets for nutrients, and even to control the calculations. The catchment outlet, i.e. the stream or the main closed drainage pipeline, would be the natural check point.

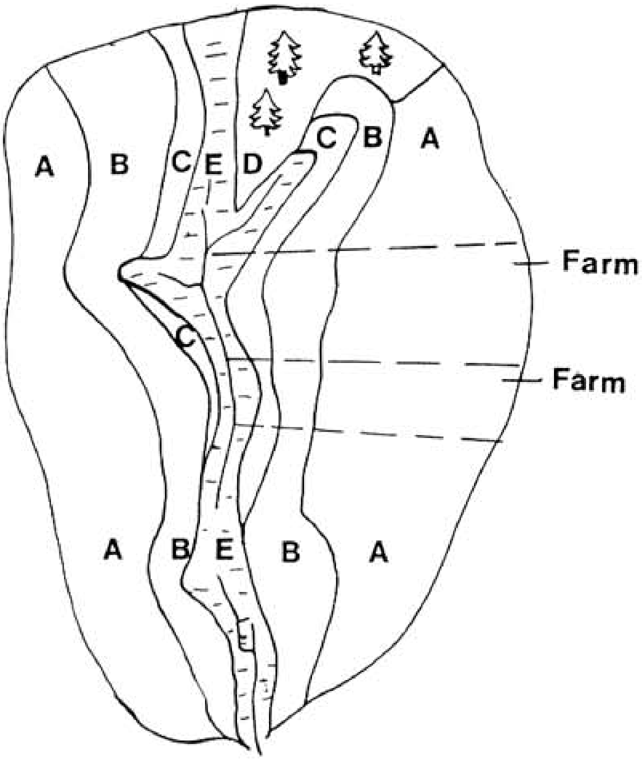
Provided with government policies and incentives for encouragement of a catchment management, farmers around a stream (waterway of first order) would be expected to approach the problems of productivity, sustainability and environment through a cooperative effort. It is to be expected that the farmers would take pride in keeping their lands productive, and their waterway clean. Therefore, an organization based on the farmers of the waterway would create the necessary feeling of responsibility directed at the productivity of the land, the quality of the environment, and the cultural landscape as a whole.

A number of measures are necessary to arrive at a clean waterway and a sustainable agricultural production:

- Balance sheets for imports of nutrients from the atmosphere, fertilizers, feeds and other sources; and exports of nutrients in milk, meat, plant products, leaching losses, etc. Derived plans for fertilizer and manure use.
- Soil conservation plan against erosion, including hydrotechnical measures, conservation tillage, etc.
- Water use plan, e.g. the need for early irrigation in cereals to ensure early uptake of nutrients (reducing risks of leaching losses at a later stage due to low yields after early summer drought).
- Plans for self-purifying measures in the low-lying areas of the catchment (permanent grass waterways, constructed wetlands, etc).
- Integrated pest management plan.

FIGURE 6
Catchment with zones of production, conservation, self-purification

Production: Intensity of cultivation, drainage, etc.
Conservation and self-purification: Forestry, wetlands - natural and constructed



Production zones
A. High intensity, e.g. cultivated once or more per year
B. Moderate intensity, e.g. crop rotation with cereals and grassland
C. Grassland

Conservation and purification zones
D. Forestry
E. Wetlands, and other areas for self-purification, wildlife, recreation

Classification for a differentiated area management

The catchment needs the normal soil survey work for base maps, or a grid sampling to provide base information for a digitized terrain model. Derived maps of erosion risk, suitability for crops, etc., are necessary to subdivide the landscape into production zones, soil and water conservation zones, and wetlands - natural and potential. The productivity zones should be classified according to suitability for, or tolerance of, different intensities, e.g. ploughing, secondary tillage, row-cropping, arable versus grassland, etc. Focus should be on limiting factors/bottlenecks. The depressions should in many cases be classified as protection zones or wetlands for self-purifying objectives (sedimentation, nutrient retention and nutrient removal).

It is possible to classify the cultural landscape in at least four dimensions:

- suitability for given productions;
- limitations due to environmental risks;
- availability of services;
- cultural value of the landscape (type, age, biological diversity 'beauty', rareness etc.).

A land unit could be assigned indexes for all four criteria. It should be noted that availability of services will show little variability within a catchment of a first-order waterway, but could be important in river basins.

Based on the suitability for production, the limitations for environmental risks, and the valuation of the cultural aspects, intensity zones for production, protection zones for environmental risk management, and zones for recreation would be developed. A schematic picture is provided by the zoning given in Figure 6. It is seen that the management zones cross the farm boundaries which calls for incentives to improve cooperative planning and management.

Integrated management

The integrated management of a catchment involves:

- integrated plant nutrition management;
- integrated soil protection management;
- integrated plant protection management;
- integrated catchment management, including water management.

The first of these management plans will be evolved on the basis of the approach outlined during this expert consultation and embraces a total management plan based on balance sheets for all sources and losses affecting plant nutrients within the catchment. Use of fertilizers, manure, other organic sources, such as plant residues and sewage sludge, catch crops, e.g. legumes, crop rotation effects, and losses, such as leaching, gaseous losses of ammonia, etc., must be considered.

The second management plan includes effects of crop rotation, soil tillage, hydrotechnical measures (contour bunds, etc.). The third management plan is outside the scope of this paper. A management plan for the catchment includes self-purification aspects through wetlands, both natural and constructed. Important measures are small, shallow lakes within streams, dams for sedimentation traps and irrigation water (especially interesting for vegetable production areas, where recirculation of nutrient rich drainage water might be an interesting environmental protection measure) and vegetation filter zones. The plan should have an approach towards making the cultural landscape more varied, more adapted to recreation.

In total, the management of the catchment according to zones of intensity of production, zones for soil protection and water protection, and zones for self-purification of surface waters, will require cooperation between farmers of the catchment. If some farmers are dairy producers, and others grain producers, it would be a challenge to distribute both grassland areas and use of manure according to the environmental requirements. At the same time there would be room for using the 'high intensity zones' for high priced products, such as vegetables.

CONCLUSIONS

A meaningful approach to combine productivity, sustainability, environmental quality, recreation and cultural landscape values is integrated management, based on the catchment of a first-order waterway (a stream or the mains of a tile drainage system) with an area of a few square kilometres. A differentiated management system, based on an intensity classification of production zones, as well as environmental classification for protection and conservation zones, would serve this purpose. Farmers would have to operate in an organized team to be able to manage by catchment.

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SESSION 6

Priorities for FAO's IPNS programme

Proposal of a framework for FAO's IPNS programme

The steady increase of the world's population entails a continuous reduction of the available arable land *per caput*. As a result, in the long run, meeting the rising needs for food will be possible only through a further intensification of agricultural production per unit area. Concurrently, special attention will need to be paid to the preservation of the productive capacity of the land and water resource base.

A major requirement for the intensification of agricultural production is a conscious effort to sustain plant nutrition through:

- the replenishment of plant nutrients taken up from the soil through harvests;
- compensation of the losses through erosion and leaching;
- enhancing the fertility status of soils that are inherently low in plant nutrients;
- rehabilitation of soils which have been depleted through 'mining'

The considerable increase in fertilizer use since the 1950s – combined with other inputs such as improved seeds, irrigation, pest and weed control – is a measure of the intensification process which has taken place, mostly in developed countries in the early stages but more recently also in developing countries. However, intensification through an increased use of inputs has met with limits on account of economic and environmental issues. Environmental hazards are mainly prevailing in industrialized countries while economic constraints are more acute in developing countries. Hence, in the field of plant nutrition, the combination of mineral fertilizers with locally-available organic sources of plant nutrients is being promoted. FAO's Integrated Plant Nutrition System (IPNS) precisely aims at the maintenance or adjustment of soil fertility and plant nutrient supply through a balanced and appropriate use of mineral fertilizers combined with organic manures, crop residues, compost, nitrogen-fixing crops, adapted to the local farming system and against the background of prevailing ecological, social and economic conditions.

Organic sources of plant nutrients can be derived from recycling, from a transfer of nutrients from non-cropped areas to arable land or, with regard to nitrogen, from biological fixation. It must be realized that practices of recycling do reduce losses but do not add nutrients to the total amount originally available. With regard to transfers it must be taken into account that, considering the low content of nutrients in fresh organic matter, the area

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PAPER 6.1

R. Dudal, Institute for Land and Water Management, K.U. Leuven, Belgium

providing nutrients needs to be relatively large to provide a substantial input. Biological nitrogen fixation requires a minimum of soil fertility – especially in terms of phosphorus and certain trace elements – for the biological process to be effective. In addition to their nutrient supply, organic inputs have shown to have beneficial effects on soil physical conditions, biological activity and efficiency of mineral fertilizers. However, it has been difficult so far to quantify these improvements and relate them to specific environments. Very often, results of experiments are difficult to transfer or extrapolate because of a lack of characterization of the site where they took place. Much of the experience gained with the use of organic inputs in temperate areas and on relatively fertile soils can hardly be applied to tropical regions where soils are much more strongly weathered and climatic conditions are strikingly different.

While mineral fertilizers are now well defined in terms of nutrient content, solubility, reaction and suitability for specific crops, organic inputs are much more difficult to qualify and quantify, the reason being the very great diversity in the nature and composition of organic inputs, the complexity of their mineralization processes, the different interactions which take place under different soil and climatic conditions. Organic materials release nutrients slowly and it is often difficult to ensure a synchronism between the nutrient supply and the demand by the crop. On the other hand, slow release of nutrients can limit losses through leaching or volatilization. Organic inputs generally require a considerable amount of labour on account of the bulk of the material that has to be collected, processed, transported and worked into the soil.

Now that the validity of an IPNS approach is generally accepted and supported, the challenge is to translate the concept into practical applications and to have it implemented at the farmers' level. It must be realized that farmers have little interest in plant nutrient management or soil fertility conservation as such. Their first priority is the sustenance of their family and the raising of their standard of living through increased production and a short-term return from their cash and labour investment. Long-term improvements or benefits are not likely to attract resource-poor farmers. The application of an integrated plant nutrition system will depend on its capacity to generate tangible yield increases and sufficient yield security which make it worthwhile for the farmer to adopt improved practices. Hence, recommendations for practical applications will need to be geared toward remedying the constraints which farmers themselves perceive and adapted to the local ecological and economic conditions. Generic or 'rule-of-thumb' recommendations would be self-defeating. Recommending the use of inputs to which the farmer has no access would not make much sense.

In order to provide advice that is tailored to a farm, or to a village or a territory, it will be necessary to establish a diagnosis of the site-specific nutrient status, to estimate the nutrient requirements for the cropping pattern that is envisaged and to assess the sources of nutrients which are available locally. In other words, advice will need to be based on a nutrient balance sheet and on an appraisal of the physical, social and economic characteristics of the site. With a view to facilitating this overall evaluation, it would be useful to have a simple, yet scientifically-based, framework to serve as a structured logical pathway for making location- and time-specific recommendations on an integrated plant nutrition for defined farming systems, taking into account both the need for sustained production and the limits to resource availability.

The framework should be designed and structured so that the considerable volume of data collected can be stored, handled and evaluated through a computer program. Such a program should be easily accessible to extension personnel, advisers and scientists. The understanding of its approach would allow them to insert their own experience into the program and adapt it, where needed, to local circumstances.

The program would need to be supported by a database which provides essential information to identify and characterize the various attributes which need to be handled in the program (e.g. crops, varieties, requirements, soils, climates, sources of plant nutrients, etc.). This database should not be tied to any specific land use or location but provide a comprehensive inventory and description of the factors that are relevant toward the formulation of judicious plant nutrition management. The program itself will include entries on the characterization of the site, the farming system, the plant nutrient budget and the cost-benefit ratio, which are specific in a particular location. At a later stage, entries covering legal, social or administrative conditions may have to be added. A breakdown of the database and of the proposed entries into the program is given below.

FRAMEWORK FOR INTEGRATED PLANT NUTRITION SYSTEMS

Database

- Crop(s) (Yield potential)
- Soils
- Climates
- Crop/soil requirements
- Crop/climatic requirements
- Mineral sources of nutrients
    - Inventory
    - Composition
- Organic sources of nutrients
    - Inventory
    - Composition
- Trace elements
    - Inventory
    - Composition
- Amendments
    - Inventory
    - Composition

Site characteristics

Location

- Situation (village, township, province, state, country)
- Longitude - Latitude

Climatic conditions

- Agro-ecological zone
- Rainfall
- Mean annual temperature
- Length of growing period

Land resources

- Soils
- Relief
- Altitude
- Constraints (erosion, flooding, wind damage, . . .)

Farming system

- Farm size
- Cropping pattern
- Land tenure
- Labour and power sources
- Tillage system
- Irrigation (if any) and water management
- Fallow period (if any)
- Level of inputs
- Infrastructure
- Income level

Plant nutrient budget

- Crop(s): single or multiple
- Yield target
- Nutrient requirements
- Soil nutrient capital: (soil testing if possible)
    - soil organic matter
    - C/N
    - N - P - K - Mg - Ca - S
    - texture
    - pH
    - CEC
- Outputs by produce
- Losses (leaching, erosion, denitrification, . . .)
- Inputs:
    - . mineral:
        - nature
        - composition
        - efficiency
        - availability
    - . organic:
        - nature
        - composition
        - mineralization rate
        - availability

  - . amendments
  - . trace elements
  - . rain
  - . irrigation water
  - . dust
  - . sedimentation

Economics

- Cost of inputs
- Labour input
- Expected benefits

Recommendation

- Sources of plant nutrients:
  - . mineral
  - . organic
- Quantities
- Timing
- Placement

It is obvious that the above list is only a 'Framework'. In order for the entries to have a bearing on a plant nutrition recommendation, they will each have to be characterized. It will need to be clearly stated how to specify land tenure, which classification of agro-ecological zones will be used, how soils will be described, how irrigation will be identified, in which way soil nutrient contents will be expressed, how the composition of nutrient sources will be determined, how mineralization rates of organic inputs will be assessed, how expected benefits will be accounted for, etc.

In addition, criteria will need to be developed for assessing the significance of each of these factors, alone or in combination, on the basis of an understanding of causes and effects and of impacts on balanced plant nutrition. In order to do so, one will need to draw heavily on common sense, experience, local knowledge, results of research and experimentation. It is fully realized that a number of entries will be approximate values only. However, the proposed pathway should make it possible to take stock of available information and to identify knowledge gaps which need to be filled. The framework approach would offer the possibility of providing objective and preliminary estimates, of acceptable reliability, without waiting for all of the final data. Even with its initial weaknesses, the framework could be a guide towards the implementation of IPNS at farmers' level. It should also help in taking advantage of many research initiatives which are now in progress and establish a link between the scientific and the farming community to ensure that recommendations that arise are feasible, profitable and acceptable.

Annex 1

Opening address

Dr H. de Haen, Assistant Director-General, Agriculture Department

Ladies and Gentlemen, on behalf of the Director-General, I welcome you all very cordially to this very important Expert Consultation. We are very pleased to see so many competent persons in this room. Among them, by the way, is one whose signature is on my undergraduate exam, when I studied at Kiel: Professor Finck. For me, it is a particular pleasure to welcome him. It is quite a long time since I was his student.

The topic of this Expert Consultation does not need explanation - certainly not to this gathering of experts. It is not even necessary to explain it to politicians and decision makers, because all are aware of the importance of sustainable agriculture, of land and water use and of the role of local and external inputs, i.e. of the relevance of Integrated Plant Nutrition Systems. Indeed many developing countries face a continuing discrepancy between the demand for and the supply of food which needs to be, at least partly, bridged by increases in production.

The recent publication "Agriculture: Towards 2010", which FAO has just presented to its Governing Bodies, predicts a continuing population growth, though slower than in the past. Still an additional 1.9 thousand million people will be in need of food between now and the year 2010. Ninety-four percent of these additional 1.9 thousand million people will be living in developing countries, many of which will not have the purchasing power, in terms of foreign exchange, to import food. They will need to rely, with regard to both their own employment and income perspectives, on domestic production. Africa will be a particular problem, where population growth is still predicted to be more than 3%, as compared to 1.5% in Asia. It is clear therefore that there will be a continuous need for growth in food production. It is estimated that the annual growth rates in agricultural production will probably be less than what they were in the last 20 years when the annual growth rate has been 2.3%. It is projected to be 1.8% in the next decade. However, to achieve this 1.8%, a considerable effort will be required in the field of plant nutrition.

Although the FAO study foresees a decline in the number of undernourished and hungry, it still predicts 650 million people hungry and undernourished by 2010, down from the 800 million of today. Meeting this challenge begins at the food production end in combination with better distribution. Regarding the sources of production growth, on average in all developing countries, 67% would arise from yield increases, 20% from area expansion and 13% from intensified cropping. It is estimated that in Africa yield increases would only contribute 53% to production growth, but 80% in South Asia. Hence a lower role of yield increases is expected where land is still available for a horizontal expansion, subject to heeding eventual ecological side effects. Deforestation is not just making arable land available but may have a number of negative implications. Yet, it is estimated that, for the next 20 years, another 100 million hectares will be converted to arable land in developing countries. If 'sustainable intensification' of production of existing land could contribute to a slowing down of this trend, this would be a valuable service to the preservation of the environment.

Intensification can have several technical bases. One option which is not sustainable is agricultural production at the cost of nutrient depletion, which leads to declining yields, particularly in sub-Saharan Africa. On the other hand, new forms of replenishing nutrients have to be developed and replenishment by merely adding mineral fertilizer is often not economically feasible and, even in a technical sense, it may not be in balance with the supply of organic matter. Moreover, nutrient replenishment by mineral fertilizers is not affordable by many farmers. This has led FAO to conceive the whole field of Integrated Plant Nutrition is a much wider context. All sources of nutrients have to be assessed, and possibly mobilized, in order to reduce the reliance on external fertilizer supply. It was this need to make soil fertility more sustainable which led to the idea of convening this Expert Consultation as a stock-taking exercise, to show where we stand and to provide guidance for future work. I will leave it to Mr. Sombroek, the Director of the Land and Water Development Division, and his colleagues to explain in more detail in which field we would like to have your advice. Let me add my personal wishes for your pleasant stay in FAO and also here in Rome.

Annex 2

Agenda

13 December 1993

08.30-09.00 hrs Registration

OPENING SESSION

Chairman: W.G. Sombroek

09.30-09.40 hrs Opening address by H. de Haen, Assistant Director-General, Agriculture Department, FAO

09.40-09.50 hrs Introductory Statement
Sustainable Agriculture: Land and water use and the role of local and external inputs for rural development, by W.G. Sombroek, Director, Land and Water Development Division, FAO

09.50-10.00 hrs Introduction of participants

10.00-10.10 hrs Organizational aspects of the meeting

10.10-10.30 hrs Coffee break

SESSION 1 Importance of plant nutrition for meeting the agricultural product requirements

Chairman: W.G. Sombroek
Rapporteur: J.C. Ignazi

10.30-10.50 hrs Development of land use and plant nutrition practices during the last 30 years – consequences for the requirements of crop productivity and plant nutrient supply up to 2010, by A.L. Angé, Chief, Plant Nutrition Management Service, FAO

10.50-11.10 hrs Integrated plant nutrition systems – basic concepts, development and results of the trial network, initiation of project activities in AGLN, and need for cooperation, by R.N. Roy, Senior Officer, IPNS, Plant Nutrition Management Service, FAO

11.10-11.25 hrs	From the fertilization of crops to the management of plant nutrients in crop rotations and farming systems: an overview, by A. Finck (Germany)
11.25-12.15 hrs	Discussions on the conceptual aspects of IPNS
12.15-14.00 hrs	Lunch break

SESSION 2 Soil organic matter, biomass, soil micro-flora, and management of integrated plant nutrition systems

Chairman: A. Njøs
Rapporteur: C. Hera

14.00-14.20 hrs	Organic and biological plant nutrient sources: potential, methods for reducing the bulk and improving the availability of nutrients, by A.C. Gaur (India)
14.20-14.35 hrs	Measurement, properties and role of the soil microbial biomass in organic matter dynamics and the maintenance of soil fertility, by P.C. Brookes (United Kingdom)
14.35-14.50 hrs	Effect of supply of organic inputs on soil fertility on western semi-arid African savannahs, by W. Burgos, Technical Officer, IPNS, Plant Nutrition Management Service, FAO
14.50-15.10 hrs	Management techniques of organic materials in sustainable agriculture, by P. Sequi (Italy)
15.10-15.25 hrs	Nutrient cycling and nutrient supply in agroforestry systems, by R.J. Buresh (ICRAF)
15.25-15.45 hrs	Tea break
15.45-16.00 hrs	Role of fallow in cropping systems of dry and humid African savannahs: maintenance of soil fertility and plant nutrient supply in crop rotation, by A.L. Angé, Chief, Plant Nutrition Management Service, FAO
16.00-16.20 hrs	Evaluation of the potential contribution of organic sources of nutrients to crop growth, by M.J. Swift (TSBF)
16.20-16.35 hrs	Technological options for controlling soil organic matter losses in tropical rainfed cropping systems, by C. Pieri (World Bank)
16.35-17.30 hrs	Discussions on the session theme
17.30 hrs	Cocktail Party, Aventino Room

14 December 1993

SESSION 3	**Renewable supply of plant nutrients from natural sources and plant nutrient transfer to crops**
Chairman:	B. van Raij
Rapporteur:	K. Harmsen
09.00-09.15 hrs	Potential and assessment of BNF and its direct contribution in selected cropping systems and ecological conditions, by Y.A. Hamdi (Egypt)
09.15-09.30 hrs	Plant nutrient supply by rain, dust, irrigation water and sedimentation - available evaluations, by S. Nortcliff (AGLS/AGLW)
09.30-09.45 hrs	Contribution of soil reserves to plant nutrient supply, by J.K. Syers (IBSRAM)
09.45-10.05 hrs	Transfer of plant nutrients and management of organic sources in China, by J. Weixu (China)
10.05-10.25 hrs	Coffee break
10.25-11.25 hrs	Discussions on the session theme
SESSION 4	**Place and role of local and external sources of plant nutrients in cropping systems and their evaluation**
Chairman:	S.K. De Datta
Rapporteur:	P.C. Brookes
11.25-11.40 hrs	Mineral fertilizers: plant nutrient content, formulation and efficiency, by C. Joly, Plant Nutrition Management Service, FAO
11.40-11.55 hrs	Efficiency of the use of nitrogen from pruning and soil organic matter dynamics in *Leucaena leucocephala* alley cropping in Southwestern Nigeria, by B. Vanlauwe (IITA)
11.55-12.10 hrs	Integrated phosphorus management: a modified Mitscherlich equation for predicting the response to phosphorus in dryland agriculture, by K. Harmsen (ICRISAT)
12.10-12.25 hrs	Contribution of nuclear techniques to the assessment of nutrient availability for crops, by C. Hera, Joint FAO/IAEA Division
12.25-12.45 hrs	Bio-availability, cycling and balances of nutrients in the soil-plant system, by N.E. Nielsen (Denmark)
12.45-14.00 hrs	Lunch break

14.00-14.15 hrs	Methodologies for comparison of local and external plant nutrition sources, by B. van Raij (Brazil)
14.15-14.30 hrs	Integrated plant nutrition in Zimbabwe, by G.G. Nleya (Zimbabwe)
14.30-15.30 hrs	Discussions on the session theme
15.30-15.50 hrs	Tea break

SESSION 5 Plant nutrient management in farming systems and in watersheds and in territories

Chairman: N.E. Nielsen
Rapporteur: R.J. Buresh

15.50-16.05 hrs	Plant nutrient balance sheets in lowland rice-based cropping systems, by S.K. De Datta (USA)
16.05-16.20 hrs	Use of organic materials and mineral fertilizers in an integrated nutrient system in French farming, by J.C. Ignazi (France)
16.20-16.35 hrs	Combined use of inorganic and organic plant nutrients in a West European arable farming system, by J.J. Neeteson (The Netherlands)
16.35-16.55 hrs	Productivity, sustainability and soil management on a catchment basis, by A. Njøs (Norway)
16.55-17.30 hrs	Discussions on the session theme

15 December 1993

09.00-10.10 hrs	Conclusions of technical sessions and discussions
10.10-10.30 hrs	Coffee break

SESSION 6 Priorities for FAO's IPNS Programme

Chairman: Y.A. Hamdi
Rapporteur: J.J. Neeteson

10.30-10.50 hrs	Proposal of a framework for FAO's IPNS programme, by R. Dudal (Belgium)
10.50-13.00 hrs	Discussions on future orientation of IPNS including priorities and methodology designs for both technical interventions and development/extension activities

13.00-14.00 hrs	Lunch break
14.00-16.00 hrs	Discussions (continued)
16.00-16.20 hrs	Tea break
16.20-16.40 hrs	Discussion on possible partners and areas of collaboration for field projects and publications
16.40-17.00 hrs	Discussion on an Expert group to assist AGLN in the implementation of the IPNS programme
17.00-17.30 hrs	Conclusions and recommendations

Annex 3

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This publication is the report of the Expert Consultation on Integrated Plant Nutrition Systems, held in Rome from 13 to 15 December 1993. The report is structured on the six main themes of the consultation: the importance of plant nutrition for meeting agricultural product requirements; soil organic matter, biomass, soil microflora and management of integrated plant nutrition systems; renewable supply of plant nutrients from natural sources and plant nutrient transfer to crops; the place and role of local and external sources of plant nutrients in cropping systems and their evaluation; plant nutrient management in farming systems and in watersheds and territories; and priorities for FAO's Integrated Plant Nutrition Systems (IPNS) programme. The summary report of the proceedings highlights the discussion papers that were presented on the different themes. It also includes the conclusions of the consultation and its recommendations for future action and collaboration.

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