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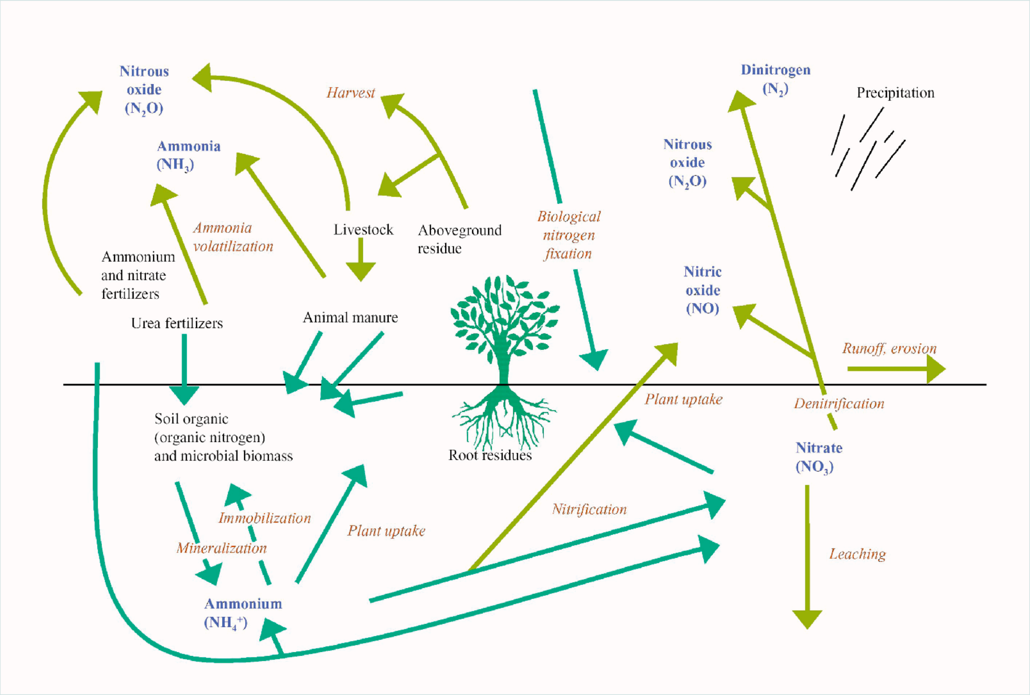
Assessment of soil nutrient balance

Approaches and methodologies



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Contents

List of tables

List of figures

Preface

Agricultural intensification without adequate restoration of soil fertility may threaten the sustainability of agriculture. Quantitative estimation of plant nutrient depletion from soils is useful for comprehending the state of soil degradation and for devising corrective measures. Nutrient-balance exercises serve as instruments to provide indicators of the sustainability of agricultural systems.

Nutrient-balance studies have used a variety of approaches and methods for different situations. However, the information has remained scattered in several publications. In order to address this issue, the Land and Water Development Division (AGL) of FAO organized an electronic conference on ‘Assessment of soil nutrient depletion and requirements - approach and methodology’ from September 2002 to July 2003. The electronic conference enabled institutions, agencies and scientists to share information and exchange ideas, views and experiences on the subject. A background document reviewing known approaches and methodologies was made available to the participants as a starting point for discussion.

This publication is the outcome of an amalgamation of the technical contents of the background paper, the inputs of the electronic conference, and further reinforcement through the latest literature and analysis. The publication presents a state-of-the-art overview of nutrient-balance studies. It brings out the evolution of the various approaches and methodologies, provides for comparisons among them, and highlights the improvements made and the issues that are still to be addressed. It categorizes case studies into macrolevel, mesolevel and microlevel classes. The macrolevel is used for national, continental and global farming-system levels. The mesolevel coincides with the level of the province, district and agro-ecological zone. The microlevel is largely defined as the farm or village level. For each case, the study explains the methodological approaches, the elements of the nutrient balance, and the calculation of the nutrient flows. Furthermore, it also discusses knowledge gaps and caveats that warrant attention.

The intention is for this publication to help bridge the scientific knowledge gap and to provide updated information on nutrient-balance approaches and methodologies to the scientific community, higher level extension workers, decision-makers, non-governmental organizations and other stakeholders concerned with agricultural development.

Acknowlegements

This document has benefited from contributions made by participants during the electronic conference on the subject. Their contributions are highly acknowledged. Special thanks are extended to R.N. Roy and R.V. Misra for their contribution to the conceptualization, organization of the electronic conference and initiation of this review. Thanks are due to J. Poulisse for his constructive suggestions. Thanks are also due to E.M.A. Smaling and J.P. Lesschen for their suggestions and contributions.

Executive summary

Soil nutrient-balance exercises based on static modelling systems and linear upscaling are devoid of the dynamics and the interacting processes involved. Methodological estimations are fraught with problems such as limited data availability at spatial scales, scale-specific spatial variation of nutrient-balance input data, non-linearity in upscaling, and lack of reliable upscaling techniques. Extrapolating present balances into the future and ensuring their validity for the future presents practical problems. There is a need for a more simple and reliable model/approach that is readily adaptable to various situations. In spite of various limitations, nutrient-balance assessments do delineate the consequences of farming for soil fertility. Of further relevance is their emergence as a reliable tool for devising time-scale soil fertility interventions based on a sound policy framework.

A recently concluded FAO-commissioned project, ‘Scaling soil nutrient balances’, and scientific interactions (FAO electronic conference, September 2002 – July 2003) have thrown further light on the critical issues concerning nutrient-balance assessment approaches. They may also help bridge methodological gaps. Further methodological refinements are feasible through making them more spatially explicit (accounting for spatial variation of soils and climate) and through improving the procedures for calculating nutrient flows and quantifying soil nutrient stocks. The introduction of mesolevel studies adds value to the existing national- and farm-level approaches. The mesolevel offers a suitable entry point for policy interventions.

Although macrolevel uncertainties need to be minimized and validations improved, it may not be possible to validate all the nutrient flows; one can focus on validating the specific flows regarded as most important. A participatory approach for the development and validation of locally specific packages needs to be promoted. Larger pools and volumes of data may facilitate refinement of the models and make them more scalable.

Intensive field checks can in part solve problems relating to data quality, map interpretation, resolution differences and groundtruthing at the macrolevel. New techniques such as reflectance spectroscopy can inject elements of precision, pace and ease into the assessment of soil properties and nutrient stocks. Classified satellite images and digital elevation models (DEMs) can bring significant improvements in mesolevel nutrient-balance studies. Stratification in sampling methods and the use of GIS for upscaling would help improve mesolevel assessments.

Presentation of the assessment outcomes in terms of yield loss or monetary values enables policy-makers to understand the issues more readily. Programmes to assist national governments in enhancing their socio-economic and policy environment for soil improvement (with the aim of promoting productive and sustainable agriculture) would be a prudent and desirable proposition.

Acronyms

AEZ	Agro-ecological zone
B	Boron
BNF	Biological nitrogen fixation
Ca	Calcium
CEC	Cation exchange capacity
CMDT	Compagnie Malienne pour le Développement des Textiles
DEM	Digital elevation model
EUROSTAT	Statistical office of the European Communities
FFS	Farmer field school
FSU	Farm section unit
GIS	Geographic information system
IAA	Integrated agriculture-aquaculture
ICRAF	International Center for Research in Agroforestry
IFDC	International Fertilizer Development Center
ILRI	International Livestock Research Institute
INM	Integrated nutrient management
ISRIC	International Soil Reference and Information Centre
K	Potassium
LAPSUS	LandscApe ProcesS modelling at mUltidimensions and Scales
LUS	Land use system
LUT	Land use type
LWC	Land/water classes
Mg	Magnesium
Mo	Molybdenum
N	Nitrogen
NUTMON	Nutrient monitoring
OECD	Organisation for Economic Co-operation and Development
P	Phosphorus
PET	Potential evapotranspiration
PLAR	Participatory learning and action research
PPU	Primary production unit
PRA	Participatory rural appraisal
QUEFTS	Quantitative Evaluation of the Fertility of Tropical Soils
RU	Redistribution unit
S	Sulphur
SPU	Secondary production unit
SSA	Sub-Saharan Africa
USLE	Universal Soil Loss Equation
WISE	World Inventory of Soil Emission potentials database
Zn	Zinc

Chapter 1
Introduction

Continuous cropping without adequate restorative practices may endanger the sustainability of agriculture. Nutrient depletion is a major form of soil degradation. A quantitative knowledge on the depletion of plant nutrients from soils helps to understand the state of soil degradation and may be helpful in devising nutrient management strategies. Nutrient-balance exercises may serve as instruments to provide indicators for the sustainability of agricultural systems. Nutrient-budget and nutrient-balance approaches have been applied widely in recent years. Studies have been undertaken at a variety of levels: plot, farm, regional, national and continental. Widespread occurrence of nutrient mining and soil fertility decline has been reported.

Most nutrient-balance studies provide rapid findings, based on a short time-frame exercise, and necessarily depend on a number of assumptions relating to system dynamics. However, questions remain concerning the validity of such assumptions, their reliability, and their capability to provide insight into dynamic processes and lend support for extrapolation. Also pertinent is the issue as to which new approaches/directions, investigations and extra efforts are required and feasible in order to enhance the validity of the assumptions and findings. Questions have been raised as to whether nutrient budgets provide the information required for understanding the status and dynamics of soil fertility across farming systems and whether such analysis may provide reliable direction and support to policy formulation on soil fertility management (Scoones and Toulmin, 1998).

SPATIAL AND TEMPORAL CONTEXT

Spatial and temporal variations in nutrient flows and budget estimations are important. For assessment purposes, a farm is usually considered as a unit even though farms comprise different soil-type entities and management regimes. Landscapes are often characterized by their diversity in terms of physical attributes and management. Contrasting soils, slopes, drainage patterns and crop husbandry situations are encountered in individual watersheds. Diversity at village levels is also evident. While field budgets could be negative, mainly because of crop harvest removals, nutrient budgets may turn positive at village level because of reasons such as manure imports. In agropastoral settings, the relationship between crop and rangeland becomes more important. Attempts to model such systems are fraught with problems and complexities especially in the context of assumptions about variables.

Temporal dynamics is another major factor with a bearing on nutrient-balance outcomes. For example, temporal variations in livestock numbers and manure production on account of migration or similar developments may lead to a significant impact on various nutrient flows, including inputs through fertilizers and manures, as well as the outflows.

In spite of such spatial and temporal dimensions, most studies opt for 'quick-find' exercises based on averages, which may have little relevance to the real picture. Thus, sampling becomes a crucial factor, and one beset with problems for nutrient-budget exercises. In addition to soil management factors, identification of the major land types, landscapes and their variability is crucial to a reliable sampling procedure. A simple summing-up of areas covered by major soil types may not provide the attributes of the diversity that exists in the farming systems.

System flows and estimations

Identification of the key inputs and outputs in various subcomponents of a bounded system is the initial step in most nutrient-budget exercises. The system boundary, its subcomponents and the various nutrient inputs and outputs are defined.

The next step is the estimation of nutrient flows either through direct measurement or through literature estimates based on standard functions. Where data are not available for a particular scale, they are extrapolated from other scales. Nutrient-budget analyses involve accounting exercises, whereby balances are calculated through summing totals for each of the nutrients identified for study.

Assumptions – their validity and reliability margins

Nutrient-budget and nutrient-balance models have to rely on a series of assumptions in order to deal with complex nutrient systems. Many nutrient-budgeting exercises treat soil-dynamics processes as a ‘black box’. The basic data for nutrient inputs and outputs are usually selected from literature and production statistics. Data from literature pertain to various sites, but may not necessarily be representative for the selected area. Some studies base their calculations on secondary data derived from certain assumptions. The data sources used for such analyses have different confidence limits attached to them. Where resource flows are translated into nutrient contents, uncertainties about data estimates also arise owing to variability in estimation procedures.

The types of input and output data that are relatively easy to measure include flows of materials, such as fertilizer, manure, crop residues and harvested grains. Several of the ‘environmental’ variables contributing to nutrient-balance calculations have to be estimated from secondary literature. Similarly, values for the export of nutrients in the harvested product are usually derived from secondary data relating to yields and nutrient contents in the harvested parts. Plant species reveal substantial variations in nutrient uptake. These depend on a number of factors such as climate, soil properties and farmers’ crop management. Export of nutrients in crop residues varies depending on residue management by the farmer, which differs greatly between and within countries. A limited number of systematic studies have examined the leaching of nitrogen (N) and potassium (K). Leaching losses have been estimated through multiple regression. Here again, there is scope for approximation and errors. Gaseous losses refer to N and may comprise denitrification and volatilization. There are few reliable data on denitrification and volatilization for the various agro-soil-climate situations. Estimates have been made using variables and multiple regressions. Processes such as erosion account for some of the important exports of soil nutrients. Substituting transfer equations from other studies sometimes leads to a wide range of results.

For data capturing at field level, one may opt for direct measurement of certain flows. However, at higher system levels, it will not be possible to measure each nutrient flow. Although primary point data may exist, calculations are required for upscaling. Where primary data are lacking, expert judgement or literature data from other geographical areas provide only ‘best guesses’.

Issues of quantification and uncertainty surround many of the nutrient transfers. The methodologies for actual field measurements of nutrient stocks are often based on nutrients in a given soil depth increment or on the concentration of nutrients in a given depth sample. The inaccuracies of the methods may result in mis-assessments. Exact determination of different soil nutrient pools is difficult because of the complex, dynamic and stochastic nature of nutrient-transformation processes in the soil system. Changes in soil nutrient stocks over time can be measured in order to form an idea about the extent of nutrient mining. However, many soil test methods do not readily reveal nutrient mining because the ‘available’ fraction extracted is buffered well by supply from other nutrient pools, as is often seen for K. Data availability only allows for a rough estimation of rates of changes in soil nutrient stocks. It does not permit long-term forecasts of soil nutrient stocks. Prognoses for the effect of soil nutrient depletion on future agricultural production are even more difficult to establish.

Upscaling and its validity

Problems arise when the scale is enlarged further to a district, national or continental scale. The aggregation of nutrient balances at field level leads to farm balances. The increasing complexity of the farm system and its architecture negatively affects the reliability of nutrient-balance calculations. Various parameters introduce elements of uncertainty into the overall nutrient balance.

The largest unit for which soil nutrient balances can be quantified is the field. Larger spatial scales can only be dealt with through generalization and aggregations. Land use systems in a region are generalized into a typology with a known or unknown variation. Aggregations then describe how the generalized, larger ‘uniform’ units are added together to yield one overall soil nutrient balance for the region. Aggregation is a delicate issue as the balance itself is made up of several parameters that are in some cases outcomes of regression analysis on more basic parameters. Model validation becomes difficult because of the lack of independent data sets that meet all the input requirements.

Socio-economic factors and their role in nutrient balances

Much of the soil nutrient debate ignores the role that farmers play in shaping the processes of environmental change. However, despite broadly similar access to resources and opportunities, marked differences often exist within a single setting in which soil fertility is handled by different farmers. Among different farmers and between areas, the relative value of land, labour and capital endowments over time may have important implications for the form and efficiency of any farm-level nutrient cycle.

Statements on soil fertility decline must refer to the relevant context. The orientation of studies towards a targeted approach to soil fertility intervention that distinguishes between farm component, agro-ecological zone (AEZ) and socio-economic groups is an appropriate approach. Non-consideration of socio-economic aspects in nutrient budget and balance studies may lead to the exclusion of many relevant factors.

Although plausible solutions may be elusive, soil nutrient-balance studies do delineate the consequences of farming for soil fertility. What is further required, and possibly more relevant, is a time-scale plan for external interventions based on a sound policy framework; this in addition to a more simple and reliable model/approach that is readily adaptable to various situations.

Chapter 2 presents a state-of-the-art overview of nutrient-balance studies at different scale levels focused on nutrient depletion. The cases are divided into macrolevel, mesolevel and microlevel scales and they are in chronological order. The scale levels are not fixed, but provide an indication of the order of magnitude. The macrolevel is used for national, continental and global farming-system level. The mesolevel coincides with the province/district/AEZ level. It can also be defined as an agro-economic entity, e.g. cotton-based or dairy-based farming systems. Finally, the microlevel is defined as the farm or village level, but it can be extended to nutrient management group or gender.

This report does not attempt to list all the nutrient-balance studies from over the years. The selection of the cases is based on the different approaches of nutrient-balance calculations and on their innovative character. For the microlevel, several cases describe a specific niche management where some fields/crops/landscape units are cherished at the expense of others. All the selected cases have been published in international journals or books. Various books and journals provide further information on nutrient balance and soil fertility related research (e.g. Smaling, 1998; Scoones and Toulmin, 1999; Smaling, Oenema and Fresco, 1999; Vanlauwe *et al.*, 2002).

Chapter 2
Methodologies for assessing soil nutrient balances

MACROLEVEL

Sub-Saharan Africa soil nutrient-balance study, FAO, 1983-2000

The study assesses the state of soil nutrient depletion in sub-Saharan Africa (SSA) for 1983 and 2000 (Stoorvogel and Smaling, 1990). It provides data on the net removal of the macronutrients N, phosphorus (P) and K from the rootable soil layer on a country-by-country basis.

The development of a method to make this assessment was the focal point of the exercise. FAO provided production figures (1983) and projections (2000) per crop and per country. These were further specified for six mainly climate-based 'land/water classes' (LWCs): low, uncertain and good rainfall areas (rainfed agriculture), problem areas, and naturally-flooded and irrigated areas. Data on fertilizer use (1983) and projections for (2000) were given per country and per crop. The next step was to define and quantify factors determining the flow of N, P and K into and out of the soil for the smallest constituents of each LWC: the land use systems (LUSs). Soil fertility dynamics in an LUS are governed by five input (IN) and five output (OUT) factors.

Methodology

Assumptions had to be made for describing and quantifying the mechanisms that contribute to the flow of N, P and K into and out of the soil. This was the pivotal stage of the exercise. An important decision in this respect was the further subdivision of LWCs into LUSs. An LUS is defined as a well-defined tract of land with its pertinent land use type (LUT) (FAO, 1976). This study included the further assumption that an LUS is a homogeneous entity. This formed the basis for calculating the nutrient balance.

Table 1 lists the attributes of an LUS. Each LWC comprises one or more LUSs. The description of an LUS is based on relevant, country-specific literature.

TABLE 1
Attributes of land use systems and their specification

Attribute	Specification
Rainfall (R)	Average for LWC (mm/year)
Soil fertility (F)	Classes: 1 - low; 2 - moderate; 3 - high
Management level	Differentiated in low (L) and high (H)
Fertilizer use	Weighting factor 0.0–3.0, related to regional distribution of total national consumption
Manure application	0, 500, 1 000, 1 500 kg/ha/year or 'during grazing'
Residue removal	% of crop residues removed from the field or burnt
Erosion	Soil loss (tonnes/ha/year)
Crops	FAO database

At any one time, a certain amount of organic and inorganic N, P and K is present in the soil in stable or labile plant-available forms. When measured one year later, these amounts are

FIGURE 1
Nutrient flows in the soil

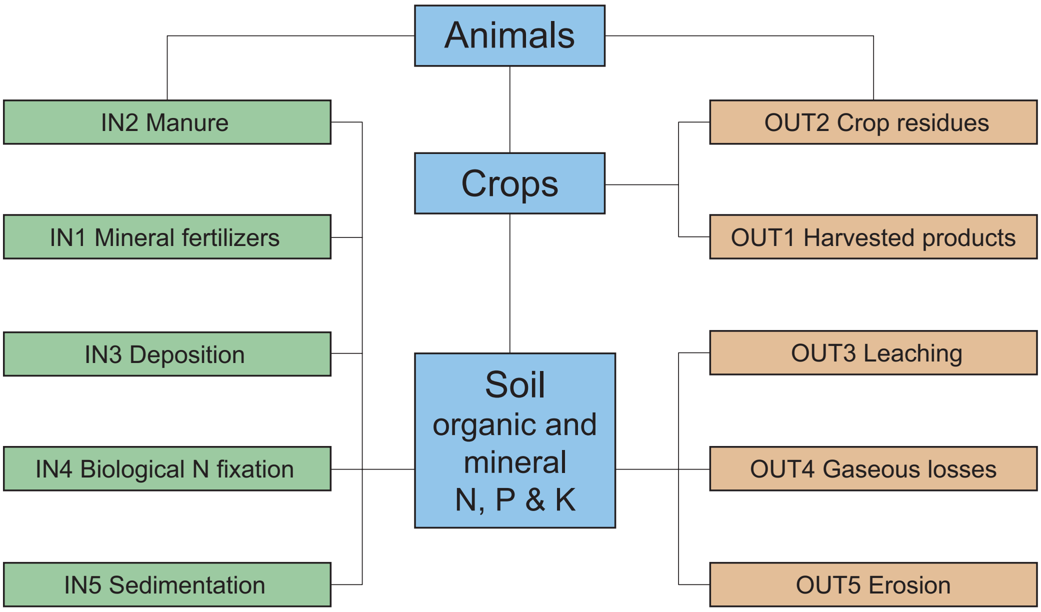


TABLE 2
Input and output factors governing nutrient flows in the soil

Input		Output	
IN1	Mineral fertilizers	OUT1	Harvested product
IN2	Manure	OUT2	Crop residues
IN3	Deposition	OUT3	Leaching
IN4	Biological N fixation	OUT4	Gaseous losses
IN5	Sedimentation	OUT5	Erosion

not necessarily the same. This is because various processes cause nutrients to flow into and out of the rootable soil layers. In spite of the uncertain nature of the many factors affecting soil fertility, a relatively simple model should serve the purpose of simulating the processes. The five input and five output factors considered in this study are listed in Table 2 and presented in Figure 1.

Eight factors have a clear role in enriching (IN) or depleting (OUT) the soil. As livestock in Africa feed largely on crop residues, the two factors IN2 and OUT2 can interact. Consequently, part of the crop residues is removed temporarily, to be returned later as manure.

Mineral fertilizers (IN1)

The FAO database contained information on actual total fertilizer consumption per crop per country for 1983 and projections for 2000. However, these data were not specified per LWC. Hence, the total amount needed to be distributed over the LWCs. Two situations arose:

1. The literature provided raw data on the regional distribution of fertilizers within a country; where so, these data were used.

2. Where such information was not available, the assumption was that the use of fertilizers was not distributed evenly within a country, and each LUS received a weighting factor as indicated in Table 3.

Table 3
Weighting factors for calculating mineral fertilizers (IN1) per land use system

Land/water class	Weighting factor	
	Low management	High management
Low rainfall (LR)	0.2	0.4
Uncertain rainfall (UR)	0.6	1.2
Good rainfall (GR)	1.0	2.0
Problem area (PR)	1.0	2.0
Naturally flooded (NF)	0.6	1.2
Irrigated area (IR)	1.5	3.0

Manure (IN2)

Although livestock is an essential element of African farming, the study did not consider extensive grazing; it considered only arable land. However, two forms of manuring occur in the LUS description:

A) Manure collection from bomas, kraals and other storage places, and application to arable fields prior to planting (LUS 0, 500, 1 000 or 1 500 kg/ha).

B) On-the-spot manuring by livestock feeding on crop residues (LUS 'during grazing'; interaction with OUT2).

In order to calculate A), each LUS with a manure input but without grazing on the arable field was characterized by one of four classes indicating the amount applied to the fields. These amounts were set at 0, 500, 1 000 and 1 500 kg fresh weight/ha/year.

Although the chemical composition of fresh manure varies widely according to its nature and moisture content, for calculation purposes it must be set at constant values for groups of LWCs. Table 4 was constructed on the scarce information available in the literature.

For B), where livestock feed on crop residues left on the field, some of the manure input is realized 'during grazing'. Three questions arose:

1. What is the fraction of the crop residues that is grazed?
2. How many hours a day do the animals spend on the grazed field?
3. What is the fraction of the nutrients that remains inside the animals?

The answers were stipulated as follows:

1. This differs for each LUS and is indicated as such in its description.
2. 12 hours (fixed value for all LUS).
3. 10 percent (fixed value for all LUS).

Table 4
Chemical composition of manure land/water classes

Land/water class	N	P_2O_5	K_2O
	(% of fresh weight)		
Low rainfall, uncertain rainfall, irrigated area	0.48	0.40	0.65
Problem area (< 1 200 mm/year rain)			
Good rainfall, naturally flooded	0.42	0.35	0.55
Problem area (> 1 200 mm/year rain)			

Deposition (IN3)

The processes of wet and dry deposition supply considerable amounts of nutrients to soils. Because of an uneven distribution of data over the continent, the calculation procedure was split into two, relating to:

1. Areas within Harmattan influence (West Africa); the literature provided sufficient point data to allow interpolation.
2. Areas outside Harmattan influence: data on the factors were scarce, but there was a correlation with rainfall; regression analysis for the different nutrients resulted in the equations listed below. They were used to calculate the contribution to soil fertility by IN3 for areas outside Harmattan influence.

   The calculations were:

   $\text{IN3 (N)} = 0.14 \times (\text{rainfall})^{1/2}$

   $\text{IN3 } (P_2O_5) = 0.053 \times (\text{rainfall})^{1/2}$

   $\text{IN3 } (K_2O) = 0.11 \times (\text{rainfall})^{1/2}$

   where: IN3 is expressed in kilograms per hectare per year; and rainfall in millimetres per year.

Biological N fixation (IN4)

An important source of N in several agricultural systems is N_2 from the atmosphere. Leguminous species and wetland rice draw considerably from this source. Based on information from the literature, three stipulations could be presented, depending on total N demand by crops:

1. Of the total N demand of leguminous crops (soybean, groundnuts and pulses), 60 percent is supplied through symbiotic N fixation (Rhizobia).
2. Of the total N demand of wetland rice (LWC, naturally flooded and irrigated area) 80 percent is supplied through chemo-autotrophic N fixation (Azolla, other algae), up to a maximum of 30 kg/ha/year. Higher uptakes are drawn from soil N.
3. All crops benefit from N that is fixed non-symbiotically (Azotobacter, Beijerinckia and Clostridium) or by N-fixing trees that are left on the field (Rhizobia and *Actinomycetes* spp.). This contribution is partitioned in Table 5.

Table 5
Contribution of scattered trees and of non-symbiotic fixation to biological N fixation

Land/water class	Input (kg/ha/year)
Low rainfall	3
Uncertain rainfall	4
Good rainfall	5
Problem area > 1 200 mm rain/year	5
< 1 200 mm rain/year	2
Naturally flooded	2
Irrigated area	2

Sedimentation (IN5)

In parts of the LWC 'naturally flooded', sedimentation takes place. Hardly any information on the nutrient content of this sediment could be traced. However, it was necessary to make an assumption on the importance of this input factor. The group of experts reached consensus on a nutrient balance being in equilibrium in this LWC. Input and output factors were calculated, but the deficit (IN5) was assumed to be supplied by the floodwater and its sediment.

In LWC 'irrigated area', the nutrient content of the irrigation water was also considered as an input factor. Literature and consultations led to the assumption that, on average, 300 mm/ha/year of irrigation water is supplied to irrigated land. The calculation of IN5 was now governed by the concentration of the three macronutrients in this amount of water. Limited information on this aspect indicated that the following values could be used:

N: 10 kg/ha/year,
P_2O_5: 3 kg/ha/year,
K_2O: 5 kg/ha/year.

Harvested product (OUT1)

Different crops withdraw different amounts of the various nutrients from the soil. A considerable amount of literature is available on this subject. Average values for each crop (excluding outliers) were compiled. In order to obtain an estimate of OUT1, these data needed to be combined with the production figures provided by FAO.

$$\text{OUT1} = \frac{\sum (\text{area} \times \text{content} \times \text{yield})}{\text{total area}}$$

Crop residues (OUT2)

An estimate of the amount of crop residues removed from the arable field was obtained from the literature. It was found that farmers' attitudes towards utilizing crop residues differed considerably among and within the countries studied. The actual removal is given in the LUS description. The removal can be complete (e.g. used for fuel, roofing or manufacturing) or incomplete (e.g. grazed or burnt). Where there was grazing, this was mentioned in the LUS description. IN2 outlines the effect of grazing on soil fertility. Burning practices are difficult to portray on a continental scale. In the study, only the residues of cotton were assumed to be burnt completely for reasons of field hygiene. Removal of N and K through burning was calculated in OUT3 and OUT4.

A complete raw data set on the uptake of nutrients by above ground crop residues was compiled. Average values of the amount of nutrients in crop residues per tonne harvested were also compiled as were ranges for several crops. Where ranges were given, the general level of management and thus the LUS description were used. The lower value of the range (few nutrients in residue per tonne of harvested product) represents a high level of management, whereas the higher value represents a low level of management. More favourable grain-straw ratios related to genetic improvements are the explanation for these differences. To calculate OUT2, the formula was:

$$\text{OUT2} = \frac{\sum (\text{area} \times \text{content} \times \text{yield})}{\text{total area}} \times \text{removal factor}$$

Leaching (OUT3)

Leaching is a significant loss mechanism for some nutrients. In tropical soils, P is often bound tightly by soil particles. Therefore, this study assumed that leaching only played a part with respect to N and K. Research on leaching is confined mainly to point observations, which have an uneven distribution over the continent. These few data are not enough to support a model that should have a spatial significance. Therefore, the literature was reviewed extensively. Together with expert consultations, this review provided clues for correlation. Multiple regression showed leaching to correlate positively with:

- R: rainfall (annual average, mm),
- F: soil fertility class (1 - low; 2 - moderate; 3 - high),
- IN1 + IN2: total application of fertilizer and manure (LUS-specific, in kg/ha/year),

and negatively with:

- UN, UK: total uptake of N and K_2O respectively (crop and yield specific, in kg/ha/year).

The following regression equations were found (in kilograms per hectare per year):

$$\text{OUT3} \quad (\text{N}) = 2.3 + (0.0021 + 0.0007 \times F) \times R + 0.3 \times (\text{IN1} + \text{IN2}) - 0.1 \times \text{UN}$$

$$\text{OUT3} \quad (\text{K}_2\text{O}) = 0.6 + (0.0011 + 0.002 \times F) \times R + 0.5 \times (\text{IN1} + \text{IN2}) - 0.1 \times \text{UK}$$

Gaseous losses (OUT4)

Table 6
'Base' denitrification per land/water class

Land/water class		Denitrification (kg/ha/year)
Low		3
Uncertain		5
Good		8
Problem	> 1 200 mm rainfall	12
	< 1 200 mm rainfall	5
Naturally flooded		12
Irrigated		11

N is lost to the atmosphere by two processes: denitrification and volatilization. Denitrification takes place under anaerobic conditions. A soil does not have to be entirely saturated for denitrification to occur. A moist soil already loses nitrate through microbial processes in wet films and pockets. The loss through denitrification is expected to be greatest in wet climates, on highly fertilized and clayey soils, and for crops that withdraw relatively small amounts of N. Ammonia volatilization plays a role mainly in alkaline environments. Because such soils are not common in SSA, volatilization and denitrification were not treated separately.

In general, information on both factors was scarce and unevenly distributed. Therefore, correlations were again sought. Multiple regression analysis provided the following equation for the output factor (in kilograms per hectare per year):

$$\text{OUT4 (N)} = \text{'Base'} + 2.5 \times F + 0.3 \times (\text{IN1} + \text{IN2}) - 0.1 \times UN$$

where:

'Base':	a constant value, covering relative wetness of the soils specific for LWCs (Table 6).
F:	soil fertility class (1 - low; 2 - moderate; 3 - high),
IN1 + IN2:	total application of fertilizer and manure (LUS-specific; in kg/ha/year),
UN:	total uptake of N (crop and yield specific; in kg/ha/year).

Erosion (OUT5)

Research findings on soil loss through erosion were reasonably well documented for most countries. An estimate of soil loss based on this information was given in the description of each LUS. A soil with a high fertility has more to lose than a poor soil. Table 7 lists the assumed nutrient contents of eroded soil material of the three fertility classes. These classes were indicated in the LUS description. They were also used to assess OUT3 (leaching) and OUT4 (gaseous losses).

TABLE 7
Nutrient contents of eroded soil at three levels of soil fertility

Soil fertility class	N	P_2O_5 (%)	K_2O
1	0.05	0.02	0.05
2	0.1	0.05	0.1
3	0.2	0.1	0.2

The difficult part was the assessment of the nutrient content in the eroded soil material. Based on the limited literature available, a so-called ‘enrichment factor’ was established. As the finest soil particles are the first to be dislodged during erosion, eroded soil material tends to contain more nutrients than the original soil. In the study, the enrichment factor was set at 2.0 for N, P and K, implying that a ratio of two between the nutrient content of the eroding soil material and the nutrient content of the original soil material.

As topsoil erodes, the roots of crops start to enter layers that were previously beyond the rootzone. Hence, part of what is lost on top is gained at the bottom of the described system. The implication is that the calculated P and K losses through erosion are offset partially by the downward extension of the rootzone. The contributions were set at 25 percent of the calculated losses for the two elements.

Cropping intensity

The FAO database provided the area values of both harvested land and total arable land for each LWC. The ratio between the two, expressed as a percentage, is called the ‘cropping intensity’ (*CI*). Where this ratio was less than 100 percent, part of the arable land was considered fallow. Its area was calculated as follows:

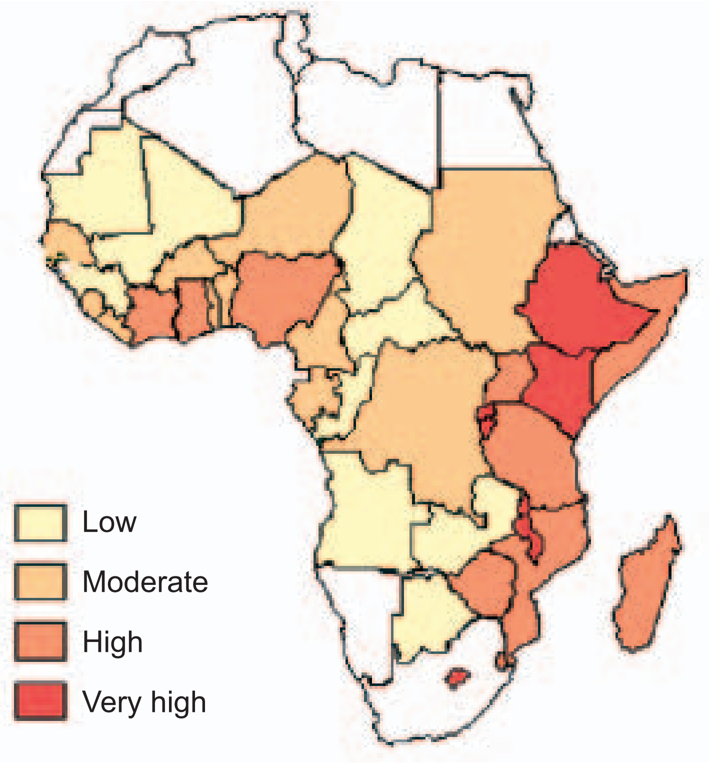
$$\text{Fallow area} = ((100/CI) - 1) \times \text{harvested area (ha)}$$

During a fallow period, a gradual buildup of nutrients takes place. IN3, IN4 and IN5 provide external contributions to soil fertility. In addition, part of the plant-available nutrients is retained in the fallow biomass instead of being leached or eroded. During years of fallow, while the ongoing processes of weathering and mineralization do not increase the total amount of nutrients in the soil, they do replenish the labile pools of the nutrients.

On the other hand, woody species from a fallow are often used as a source of fuel or sold along the roadside (OUT1), a fallow is partly depleted by grazing animals that do not return all they have taken (OUT2 – IN2), and the slash and burn practices prior to cultivation enhance the loss processes OUT3-OUT5 strongly. In addition, extra input in West Africa through deposition of dust (IN3) is offset by extra output owing to the scarcity of fuelwood (OUT1).

These considerations, combined with findings in literature and expert consultations, led to the decision to set the nutrient input by fallow at fixed values of 2 kg/ha/year for N, 2 kg/ha/year for P_2O_5, and 1 kg/ha/year for K_2O irrespective of the LUS. Where cropping intensity equalled 100 percent, the fallow acreage was set at 0 ha. Where the cropping intensity exceeded 100 percent, multiple cropping took place and it was assumed that there was no fallow. In this

Figure 2
Nutrient depletion rate in sub-Saharan Africa, 1983



case, the harvested areas and yields of the annual crops were adapted so that the total area equalled the arable area, and the total production remained the same.

Results

The results of the study showed N, P and K balances by land use system and by country. They revealed a generally downward trend in soil fertility in Africa. Densely populated and hilly countries in the Rift Valley area (Kenya, Ethiopia, Rwanda and Malawi) had the most negative values (Figure 2), owing to high ratios of 'cultivated land' to 'total arable land', relatively high crop yields and erosion. For SSA as a whole, the nutrient balances were: -22 kg/ha in 1983 and -26 kg/ha in 2000 for N; -2.5 kg/ha in 1983 and -3.0 in 2000 for P; and -15 kg/ha in 1983 and -19 kg/ha in 2000 for K. Table 8 lists nutrient balances for several SSA countries. The prediction for 2000 was for a more negative nutrient balance for almost all countries. This was influenced by the optimistic FAO estimates for crop production in 2000 (high OUT1) and the expected decrease in fallow areas in 2000.

Discussion

Following earlier work by Pieri (1985), this study was the first with a clearly defined nutrient balance and quantified nutrient flows. It has formed the basis for most subsequent nutrient-balance studies. The basis of the nutrient balance with five inflows and five outflows has been used widely. However, other studies with different data availability and objectives have modified the calculation of some flows.

Table 8
Average nutrient balances of some sub-Saharan African countries

Country	N		P		K	
	1982-84	2000	1982-84	2000	1982-84	2000
	(kg/ha/year)					
Benin	-14	-16	-1	-2	-9	-11
Botswana	0	-2	1	0	0	-2
Cameroon	-20	-21	-2	-2	-12	-13
Ethiopia	-41	-47	-6	-7	-26	-32
Ghana	-30	-35	-3	-4	-17	-20
Kenya	-42	-46	-3	-1	-29	-36
Malawi	-68	-67	-10	-10	-44	-48
Mali	-8	-11	-1	-2	-7	-10
Nigeria	-34	-37	-4	-4	-24	-31
Rwanda	-54	-60	-9	-11	-47	-61
Senegal	-12	-16	-2	-2	-10	-14
United Republic of Tanzania	-27	-32	-4	-5	-18	-21
Zimbabwe	-31	-27	-2	2	-22	-26

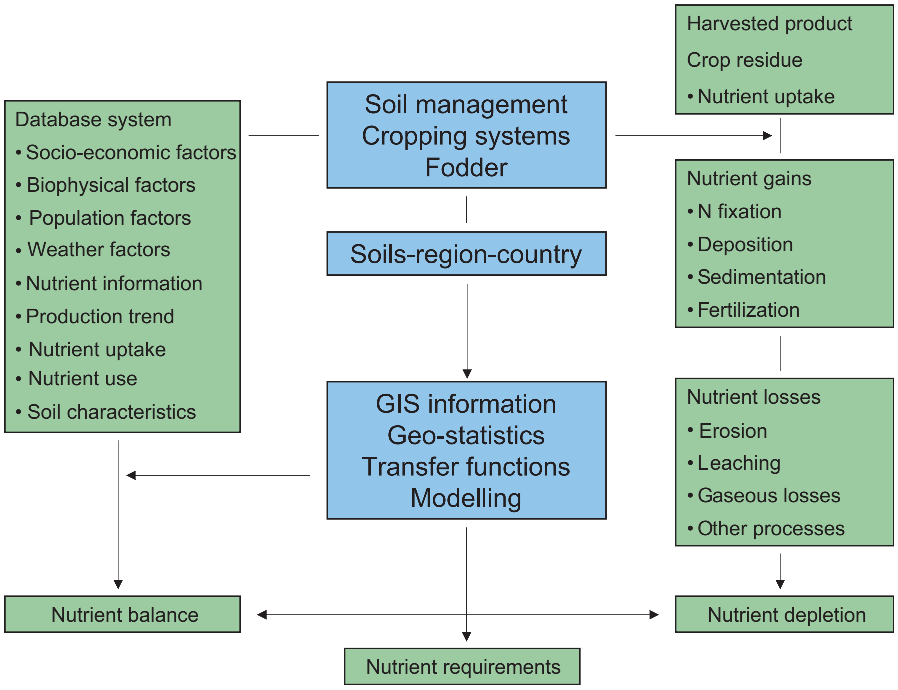
Nutrient-balance studies in Africa, IFDC approach

The methodological approach used by the International Fertilizer Development Center (IFDC) to estimate nutrient balances, depletion rates and requirements combines information on agricultural production, soil characteristics and biophysical constraints with methods and procedures designed for making such estimates (Henao and Baanante, 1999). The information and data related to agricultural production include land use, population-supporting capacity of land, crop production, and use of mineral and organic fertilizers. The approach uses attribute and geographic database systems in conjunction with empirical and mechanistic models to produce information for analyses and monitoring.

The approach builds upon previous work on nutrient balances (Stoorvogel and Smaling, 1990; Smaling and Fresco, 1993; Smaling, Stoorvogel and Windmeijer, 1993). This building on previous work involves the linking of methods and procedures for estimating nutrient balances with attribute databases and geographic information systems (GIS). It integrates data and information in a common geo-referenced base, and illustrates in the form of maps and graphs estimates of nutrient balances and rates of nutrient depletion from soils of agricultural lands at country and regional levels. Figure 3 presents a flowchart of the approach used to integrate the various components into a geo-referenced system for estimating nutrient depletion and nutrient requirements.

Attribute data include crop areas and levels of production, as well as nutrient uptake for ten crop groups that include 90 major food and industrial crops. The crops included in the database account for about 95 percent of the total cultivated area in Africa. Uptake rates for N, P and K for each crop are estimated using data from field studies. The database includes time series data on crop production and areas for the period 1961–1995 (FAO, 1994) and on mineral fertilizer consumption by country and region for the period 1985–1995. Information on organic fertilizer use and practices is also a component of the database. Combined with information on crop

Figure 3
Geo-referenced system for estimating nutrient depletion and requirements



and soil management systems, soil constraints, soil characteristics and climate by region and country, these data have been assembled into a database management system.

Methodology

A simple specification of the balance of nutrients (N, P and K) in soils of agro-ecosystems at a country or regional scale is given by the following equation:

$$Rn_{tn} = \sum^{tn} (AP_t + AR_{\Delta t} - RM_{\Delta t} - L_{\Delta t}) \qquad (1)$$

where: Rn_{tn} is the quantity of inorganic and organic nutrients remaining in the soil at time tn; AP_t is the soil inorganic and organic nutrients present at time t; $AR_{\Delta t}$ is the inorganic and organic nutrients added or returned to the soil during the time interval Δt. The $RM_{\Delta t}$ estimate is the plant nutrients removed with the harvested product and residue management during the time interval Δt, and $L_{\Delta t}$ is the inorganic and organic nutrients lost during the time interval Δt. The value of t represents the beginning time period, tn represents the ending time period, and Δt is the time interval between t and tn.

Equation 1 states that if the amounts of nutrients removed from the soil (outflows) are greater than the additions (inflows) either by fertilization or management practices, then the reservoir or stock of nutrients within the soil pool will decline. Exact determination of different soil nutrient pools is difficult because of the complex dynamic and stochastic nature of nutrient transformation processes in the soil system.

The production of crop outputs and residues is used to calculate total crop nutrient uptake from soils. Nutrient depletion and requirements are assessed by calculating and using estimates of nutrient gains attributable to the application of mineral and organic fertilizers and to biophysical processes of deposition, sedimentation and fixation. Information on weather, soil constraints, soil characteristics and AEZs is used to estimate soil nutrient losses resulting from erosion, leaching and volatilization (gaseous losses). Estimates of nutrient gains and losses are developed from assumed soil nutrient transfer functions and from estimation of empirical statistical models.

Empirical nutrient loss models and transfer functions are estimated and used to calculate removal and assess nutrient losses through various mechanisms and processes. Further research and improvements in data should enhance the reliability of these models as predictors of nutrient transfers and losses through various processes. The specification and estimation of these models are described below.

Harvested product (Nu)

The harvest of crop outputs and removal (export) of crop residues are major mechanisms of nutrient removal. Average values of N, P_2O_5 and K_2O uptake were obtained from the literature and experimental data. The nutrient uptake (Nu) in harvested product j and country i was calculated by multiplying total crop production (Cp_{ij}) by the crop nutrient uptake index (NI_j), expressed in kilograms per tonne:

$$Nu_{ij} = Cp_{ij}\,(NI_j) \qquad (2)$$

Values of crop nutrient uptake indices (NI_j) were derived from the literature and from experimental results. These indices were estimated for crop yields of traditional and improved crop varieties under average management conditions.

Crop residues (Nr)

Indices of content of N, P_2O_5 and K_2O in crop residues were obtained from references and field studies. The nutrient removed from the soil by crop residues was calculated by multiplying the nutrient content in the residue (NI) by the crop production data (Cp) for countries and regions, the harvest index (HI) and the approximated percentage of residue left on the soil after crop harvesting (Ref). Thus, the amount of nutrient uptake in the residue removed from soil for a given crop (j) in a country/region (i) is determined by:

$$Nr_{ij} = Cp_{ij}\,(1\text{-}HI_j)\,NI_j\,Ref_j \qquad (3)$$

where Nr_{ij} represents the nutrient uptake in crop residues, in tonnes or kilograms per hectare, depending on the crop production values. Estimates of the amount of residue left on the soil after harvesting and grazing were obtained from references and country reports. The harvest index (HI) measures the proportion of the economically produced part of the biomass that is actually harvested.

Leaching of nutrients (Nl)

Most of the literature on nutrient leaching is confined to information on point observations for N and K, which are variable and difficult to extrapolate. The literature reveals that N leaching can be predicted reliably in an African environment on the basis of information on rainfall, soil moisture content and nutrient content of the soils. Regression models have been estimated to predict nutrient leaching at country and regional levels. The general specification of this model includes as variables: the fertility of the soils expressed as soil fertility class (Fc), the average rainfall (R) for the region/site, and the nutrients applied (Cn). The model was specified as follows:

$$Nl_i = \alpha + (\beta_1 + \beta_2 R)\, Fc + \beta_3 \log(R) + \beta_4\, Cn + \in_i \qquad (4)$$

where: $100 < R < 3\,300$; Nl_i is the amount of leaching of N or K at site i, expressed as percentage of the quantity applied; the parameter estimates α, β_1, β_2, β_3 and β_4 measure the effects of site management, soil fertility class (Fc), rainfall (R), and nutrient applied in the form of mineral and organic sources (Cn), respectively. The soil fertility class Fc is included to account for the fertility and management of the soil as determined by soil classification and the availability of soil nutrients. This is assessed broadly as: 1 = low; 2 = moderate; and 3 = high. The parameter $\in_i$ is the error associated with the estimation of the model.

Nitrogen gaseous losses (Ng)

Experimental data were used to predict denitrified soil N in Kenyan soils. Losses of N through ammonia volatilization can also occur in tropical areas with high use of fertilizer and organic sources of N. Such losses are influenced mainly by: soil texture, pH, and climate factors. Nutrient losses through both mechanisms are included in calculating N balances. A model has been specified to predict these N losses. This model includes as variables: rainfall, soil fertility class to account for soil factors, and the quantity of nutrients applied as a proxy of N availability. The estimating model used has the same form as that in Equation 4. N losses in the model are measured as percentage of the total N uptake. Parameter estimates α, β_1, β_2, β_3, and β_4 have a similar interpretation and meaning as in Equation 4 but, for this purpose, with respect to the measure of N loss (Ng).

Soil erosion (Ne)

There is abundant information in the literature on the amount of soil eroded by water in different areas and soil types of Africa. Many different factors interact to determine the amount of soil loss occurring at a particular time and place. The Universal Soil Loss Equation (USLE) describes the impact of the most important factors (Wischmeier and Smith, 1978). Estimates of soil erosion have been obtained by using the USLE and available data. This model estimates soil erosion in tonnes per acre per year as a function of: a rainfall erosivity index, a soil erodibility factor, topographic factors of slope gradient and length, and a land cover and crop management factor. The cropping and management factor is a composite of: the effects of crops and crop sequence, tillage practices, and the interaction between these factors and the timing of rainfall through the year.

Wind and water can transport soil. Erosion by wind is noticeable in the dry areas of Africa (North and sub-Saharan). Empirical equations have been derived to estimate soil erosion caused by wind. These equations require data on wind velocity, precipitation and moisture indices (Lal, 1985; FAO, 1976). General functional relationships between factors that affect wind erosion have been included in the wind erosion equation. This equation specifies soil loss in tonnes per acre year as a function of: a soil erodibility index, a soil-ridge roughness factor, a climate factor, the field length along the prevailing wind erosion direction, and an index of vegetative cover.

Where reliable information is available, estimations of soil erosion by water can be derived using the soil loss erosion models. However, in this study, very few data were available to use the wind equation or to estimate soil erosion by wind. Enrichment values (nutrient adsorbed on soil particles) were used from empirical models and table of references to convert soil erosion losses to nutrient losses. Estimates of nutrient losses due to erosion were obtained for country and regional levels by using the following regression function model to adjust and predict the amount of nutrient eroded (*Ne*):

$$Ne_i = \alpha + \delta_1 + \delta_2 + \beta_1 Fc + (\beta_2 + (\beta_3 Fc)\, Cn + \in_i \qquad (5)$$

where: Ne_i is the percentage of nutrient loss through soil erosion in the selected crop/region; and α, δ_1 and δ_2 are parameters measuring the effects of factors that are not included in the models but characterize the Sudano-Sahelian, humid, and subhumid regions, respectively. These factors characterize and are specific to each of the countries/regions. The parameters β_1, β_2 and β_3 measure the effects of the soil fertility class (*Fc*) and the mineral and organic nutrients applied each cropping season (*Cn*) on the amount of nutrient eroded. The variable $\in_i$ is a random error.

Assessment of nutrient inputs and inflows

In order to assess the use of mineral fertilizers (*Mf*), information on nutrient applications per country in tonnes of N, P_2O_5 and K_2O was obtained from the FAO database (FAO, 1996). Weighting factors and GIS routines were used to calculate fertilizer use at higher levels of aggregation (region, soil class, land use class, AEZ, etc.).

The data required to calculate organic nutrient inputs (*Of*) (mainly in the form of animal manure) include: the livestock population; the amount of manure reaching arable land; and the nutrient content of the manure at the time of application. However, additional information is required to estimate recycling of household waste and industrial refuse. Some of these data are often not readily available at country and regional levels.

Information from the literature on type of manure and organic products, rates of application by farmers, and livestock production practices in selected regions and countries was used to estimate the amounts of nutrient inputs provided by the use of organic fertilizers.

Country-level estimates of the amount of nutrient returned to the soil in the form of solid manure were calculated on the basis of: the amount of residue left on the field that is grazed, the nutrient content of the residue, and the fraction of nutrients from the residue that remains inside the animal. The value of this fraction used in the estimations presented in this paper was 10 percent.

The amounts of nutrients that return to the soil by deposition (*Nd*) are difficult to estimate. Deposition is associated mainly with the levels of nutrients used (and produced) and with the amount of rainfall. Wet and dry depositions were evaluated for selected sites using transfer functions. A model was estimated by using forms of empirical functions from other studies (Stoorvogel and Smaling, 1990; Smaling and Fresco, 1993). In those studies, nutrient deposition is specified as a function of the square root of average annual rainfall. Therefore, the following model was estimated and evaluated in this study:

$$Nd_i = \alpha + \delta_1 + \delta_2 + \delta_3 + \beta_1 Fc + (\beta_2 (R)^{\frac{1}{2}} + \in_i \qquad (6)$$

where: Nd_i is nutrient deposition as a percentage of total nutrients; α, δ_1, δ_2 and δ_3 are parameters of discrete variables included to account for variability due to regional factors; β_1 is the parameter measuring the effect of soil fertility on nutrient deposition; β_2 is the parameter measuring the effect of rainfall on nutrient deposition; and $\in_i$ is the error term.

The mechanism concerning inputs of nutrients due to soil sedimentation (*Ns*) is particularly important in irrigated areas and on naturally flooded soils. Quantification is a difficult task because of the lack of sufficient information on the nutrient content of sediments. Because of this limitation, values in kilograms per hectare per year of the amounts of nutrients in irrigation water were used for selected regions and crop systems.

Regarding N inputs due to N fixation, information in the literature about the nature of N uptake by crops was used to identify three basic distinctive scenarios determined by the nature of N uptake by crops:

- About 60 percent of the total N uptake by leguminous crops (soybeans, groundnuts and pulses) is supplied through symbiotic N fixation.
- About 80 percent of the total N demand of wetland rice, up to a maximum of 30 kg/ha/year, is supplied through chemo-autotrophic N fixation.
- All crops benefit from N that is fixed non-symbiotically or by N-fixing trees that are left growing in the fields. Contributions of non-symbiotic fixation to N requirements of crops are negligible in the arid and semi-arid regions. N fixation by trees has been estimated at 2–10 kg/ha, of which about 25 percent is expected to return to the soil.

Assessment of nutrient depletion and requirements

The quantity or rate of nutrient depletion is estimated as the difference between the amount of nutrients exported annually from cultivated fields and the amount added or imported annually in the form of fertilizers, manure, fixation, and the physical processes of deposition and sedimentation. The balance of nutrient inflows and outflows (Nb_i) per year or nutrient depletion in kilograms per hectare per year for a country (*i*) and crop (*j*) is assessed and estimated as follows:

$$Nb_i = \Sigma_{ij}\,(Mf_{ij,}\ Of_{ij,}\ Nf_{ij}) + \Sigma_i\,(Nd_i, Ns_i) - (\Sigma_{ij}\,(Nu_{ij}, Nr_{ij}) + \Sigma_\mathrm{i}\,(Nl_i, Ng_i, Ne_i)) \tag{7}$$

The calculation of nutrient requirement is indicated by:

$$Nur_i = \Sigma_{ij}\,(Cp_{ij})\,(NI_j) + \Sigma_{ij}Nr_{ij} + \Sigma_i\,(Nl_i, Ng_i, Ne_i) \tag{8}$$

The nutrient requirement (Nur_i) is calculated as the amount of nutrient uptake required to achieve a specific target yield without depleting the soil nutrient. The calculated nutrient uptake requirements are minimum requirements. A crop could take up more than Nur_i and this would result in increased production or yield or improved quality of the product. As necessary, the model is adjusted by the available soil nutrient content. Furthermore, in order to estimate the amount of a fertilizer product required, the nutrient requirement is adjusted to account properly for the fraction of fertilizer nutrient that is actually taken up by the crop (fertilizer use efficiency).

Average rates of nutrient depletion and nutrient requirements were estimated initially at a macroscale for each country in Africa. Because of significant variability within countries, estimates were calculated for selected areas within countries using more elaborated transfer functions, empirical response models, and geostatistical routines.

Results

Nutrient depletion rates were calculated for all African countries (Table 9). The balances were negative for all countries except Mauritius, Réunion and the Libyan Arab Jamahiriya. The nutrient balance ranged from -14 kg NPK/ha/year for South Africa to -136 kg NPK/ha/year

TABLE 9
Average level of NPK balances, 1993–95

	High (> 60)	Medium (30-60)	Moderate/low (< 30)
	(kg NPK/ha/year)		
Burkina Faso	Mali	Benin	Algeria
Burundi	Mozambique	Cape Verde	Angola
Cameroon	Nigeria	Central African Republic	Botswana
Côte d'Ivoire	Rwanda	Chad	Egypt
Dem. Rep. Congo	Senegal	Congo	Morocco
Ethiopia	Somalia	Equatorial Guinea	South Africa
Gambia	Swaziland	Gabon	Tunisia
Ghana	Uganda	Lesotho	Zambia
Guinea	United Republic of Tanzania	Mauritania	
Guinea-Bissau		Niger	
Kenya		Sierra Leone	
Liberia		Sudan	
Madagascar		Togo	
Malawi		Zimbabwe	

for Rwanda. The N and K losses were associated primarily with leaching, soil erosion and low recycling of crop residues. Losses of P were associated mainly with soil erosion.

Discussion

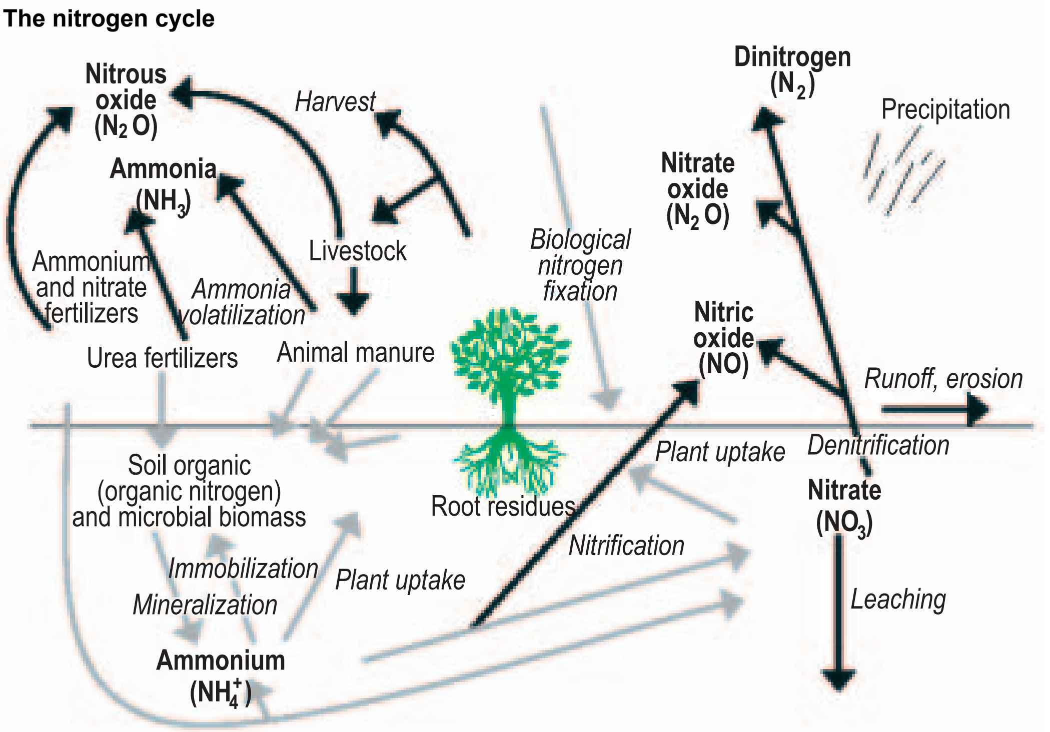
The methodological approach of the study by Henao and Baanante (1999) was based on Stoorvogel and Smaling (1990). The same nutrient flows were used and the calculation of the flows was similar although a different notation was used. The innovative aspect of this study is the link with a database and GIS system, which makes the nutrient-balance calculations much easier and faster. Calculations can be made for each year as the data is based only on FAOSTAT and GIS maps, while Stoorvogel and Smaling (1990) used a unique data set with soil/water classes and LUSs. However, the calculation is still on a country basis and differences within the country are not shown. The GIS and database system offer the possibility to link with decision-support systems and crop growth models, but this has not been done yet.

National soil surface nitrogen balances, OECD

The issue of agricultural nutrient use has been a priority issue for the Organisation for Economic Co-operation and Development (OECD) in developing a set of agri-environmental indicators as part of the analysis of the interactions between agriculture and the environment and the impact of changes in agricultural policy on the environment.

The major environmental issues associated with N surpluses from agriculture include pollution of surface water, groundwater and air. However, a deficiency of soil N can also impair the resource sustainability of agriculture through soil degradation and soil mining, resulting in declining fertility in areas under crop or forage production. In cooperation with the statistical office of the European Communities (EUROSTAT), the OECD is in the process of improving and updating the N balances presented here (OECD, 2001a). The work is also being extended to cover P balances.

FIGURE 4
The nitrogen cycle



Note: Grey arrows represent N inputs and black arrows represent N outputs. The different forms of N are in bold text and the processes of N transformation are in italics.
Source: OECD, 2001a.

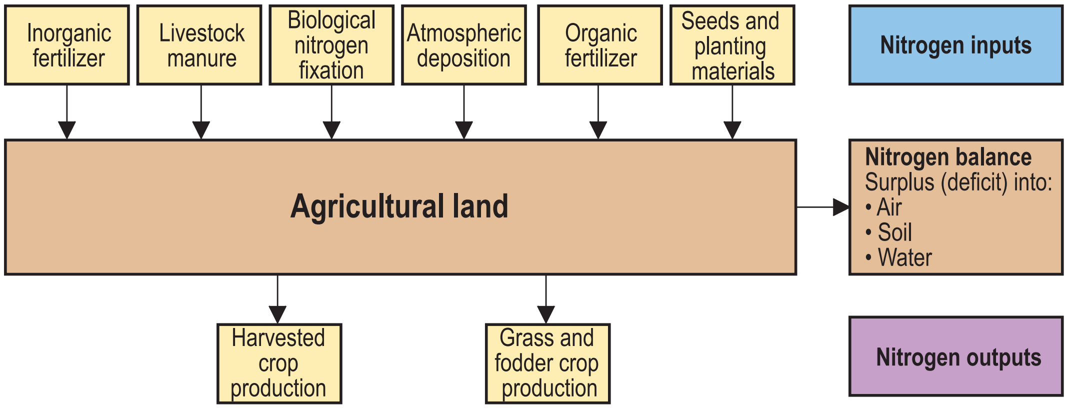
Methodology

The OECD soil surface N balance calculates the difference between the total quantity of N inputs entering the soil and the quantity of N outputs leaving the soil annually, based on the N cycle (Figure 4). Therefore, N loss directly from livestock (e.g. ammonia volatilization from stored manure) is not included in the balance, although livestock manure production is a major source of N input; this affects the balance. The excess or surplus N may remain in the soil, leach into groundwater and volatilize into the air.

The estimate of the annual total quantity of N inputs for the soil surface N balance includes the addition of:

- inorganic or chemical N fertilizer: quantity consumed by agriculture;
- livestock manure N production: total numbers of live animals (cattle, pigs, sheep, etc.) in terms of different categories according to species (e.g. chickens, turkeys), sex, age and purpose (e.g. milk cow, beef cattle), multiplied by respective coefficients of the quantity of N contained in manure per animal per year;
- atmospheric deposition of N: total agricultural land area multiplied by a single coefficient of N deposited per hectare;
- biological nitrogen fixation (BNF): planted area of legume crops or pasture (e.g. field beans, soybeans, clover, alfalfa and pasture) multiplied by respective coefficients of N fixation per hectare, plus the N fixation by free-living soil organisms computed from the total agricultural land area multiplied by a single coefficient of N fixation per hectare;

FIGURE 5
The main elements in the OECD soil surface N balance



Source: OECD, 2001a.

- N from recycled organic matter: quantity of sewage sludge applied to agricultural land multiplied by a single coefficient of N content of sewage sludge;
- N contained in seeds and planting materials: quantity of seeds and planting materials (e.g. cereals and potato tubers) multiplied by respective coefficients of N content of seeds per planting materials.

The estimate of the annual total quantity of N outputs**,** or N uptake, for the soil surface N includes the addition of:

- harvested crops: quantity of harvested crop production (e.g. cereals, root crops, pulses, fruit crops, vegetables and industrial crops) multiplied by respective coefficients of N uptake to produce a tonne of harvested crop;
- harvested forage crops: quantity of harvested forage crop production (e.g. fodder beets, hay and silage) and grass consumption from temporary and permanent pasture multiplied by respective coefficients of N uptake to produce a tonne of forage.

The OECD soil surface balance calculation is not a gross calculation of all N losses from agriculture (Figure 5). This is because the focus is on N losses to soil and water as volatilization of ammonia from stored manure and livestock housing is excluded from the calculation.

The basic data in the database are preliminary, and data definitions may vary across countries following the definitions in the original surveys. For example, although crop production data generally refer to the normal state of the specific crop unless otherwise stated (e.g. dry weight for cereals, fresh weight for vegetables), forage production may refer to weights with different moisture contents across countries.

The coefficients used for the calculation are preliminary and their derivation may vary across countries. In any case, the definition of coefficients should meet the definition of the corresponding basic data.

The database consists of four parts (Figure 6):

- fertilizer/headage/crops: basic data to calculate the N balance, covering the N inputs and outputs in the soil surface balance;

FIGURE 6
Summary of database structure

Basic data on fertilizer / headage / crops	Coefficients	Quantity of nitrogen	Nitrogen balance
Fertilizers: inorganic and organic products (excluding livestock manure)	Fertilizers kg nitrogen / tonne of fertilizer	Fertilizers	Calculation of the total nitrogen balance and the balance/ha
Livestock (number of live animals)	Livestock manure kg nitrogen / head / year	Livestock manure	
Manure withdrawals from agriculture, manure stocks and imports	Manure withdrawals stocks and imports kg nitrogen / tonne of manure	Manure withdrawals, stocks and imports	
Harvested crop production	Harvested crops kg nitrogen uptake / tonne of crop	Nitrogen uptake by harvested crops	
Forage production	Forage kg nitrogen uptake / tonne of forage	Nitrogen uptake by forage	
Seeds and planting materials	Seeds and planting materials kg nitrogen / tonne of material	Nitrogen contained in seeds and planting materials	
Area of legume crops	Biological nitrogen fixation kg of nitrogen / ha of legume crop area and total agricultural area respectively	Biological nitrogen fixation	
Agricultural land use area	Atmospheric deposition kg nitrogen / ha of agricultural land	Nitrogen fixed from atmospheric deposition	

- coefficients: to convert basic data (e.g. livestock numbers) into N equivalents;
- quantity of N: N content, involving the multiplication of the basic data by the N coefficients, to provide the total N content for the N input and output items;
- N balance: covering the main categories of N inputs and outputs, the N balance calculation (inputs minus outputs), and the expression of the N balance in kilograms of N per hectare of agricultural land.

The classification system of crops and livestock draws on the original data sets, i.e. national sources, EUROSTAT (for European Union member countries) and FAO.

Disaggregated data are provided where possible, especially for crop and livestock series, in order to facilitate a more accurate estimate of the N balance (e.g. piglets and sows), plus the relevant subtotal (e.g. total pigs). However, where disaggregated data do not exist, then aggregated data are provided (e.g. total pig numbers), together with the corresponding coefficients to convert these data into N composition and quantities.

Countries use different classification systems to record the numbers of live animals, especially for cattle, pigs and poultry.

Fertilizers

This category covers data on apparent inorganic fertilizer consumption and on other organic fertilizers applied to agricultural land, excluding livestock manure, which is treated separately.

Inorganic fertilizer consumption includes:

- nitrogenous fertilizers, covering consumption of nitrogenous fertilizers, expressed in N content.

Organic fertilizers include:

- sewage sludge, covering use of treated public sewage sludge;
- urban compost, covering use of urban compost from public refuse collection;
- industrial waste products, covering use of industrial waste, such as products from the food processing industry;
- other products, covering other organic products used as fertilizers.

Livestock numbers

This category covers the total livestock inventory of live animals required in the calculation of the N content of livestock manure production. The numbers of live animals include those recorded for a given census day in the year, and do not include the total numbers of animals slaughtered in a given year. The total numbers of livestock slaughtered in a year are reflected in the coefficients used to convert livestock numbers into N content in manure. The livestock categories covered include:

- cattle, covering beef cattle, dairy cattle and calves;
- pigs, covering pigs of various ranges of weights;
- sheep and goats, covering sheep, lambs and goats;
- poultry, covering chickens for broilers and layers, and other poultry, such as ducks and turkeys;
- other livestock, covering other livestock, such as horses and donkeys.

Manure withdrawals, stocks and imports

This category covers data on: livestock manure withdrawn and not used on agricultural land (including manure exports); the increase or decrease of manure stocks intended for use on agricultural land; and manure imported into a country for use on agricultural land. This information provides the basis for calculating the ‘net’ input of livestock manure on agricultural land in given year as follows:

Net input = livestock production - withdrawals + change in stocks + imports

Manure withdrawals represents the amount of manure withdrawn from agriculture and not applied to agricultural land. The volatilization of ammonia and mineralization of N after applying manure to the soil are regarded as a part of nutrient losses (or nutrient surplus) and are not included in this category. On the other hand, destruction of manure and volatilization of ammonia from stored manure, livestock housing and manure-spreading operations are excluded from the balance. The manure categories are:

- destruction and evaporation, covering destruction of manure and volatilization of ammonia that occurs from stored manure, livestock housing and manure-spreading operation;
- non-agricultural use of manure, covering areas such as private gardens;
- processed as industrial waste, covering manure processed as industrial waste in a processing plant and not used on agricultural land;

- exported organic fertilizers, covering manure and other organic fertilizers exported from a country;
- other withdrawals, covering other manure withdrawals;
- change in manure stocks, covering change in livestock manure stocks, obtained by deducting the opening stocks from the closing stocks;
- imported organic fertilizers, covering manure and other organic fertilizers imported.

Harvested crops and forage

This category covers data on: harvested crop production from arable field crops (e.g. cereals); permanent crops (e.g. citrus fruits); forage production, including both harvested fodder crops (e.g. fodder beets); and pasture production from temporary grassland and permanent pasture. The definitions and categories of crops and forage follow closely those used by FAO. While many countries have disaggregated fruit and vegetable production data, these are included only where coefficients exist to convert the particular fruit or vegetable into its nutrient content and composition.

Harvested crops, regardless of their final destination, include those for human consumption, livestock feed, industrial use and seeds:

- cereals, covering wheat, rice and coarse grains;
- oil crops, covering annually sown oil crops (e.g. soybeans), perennial oil crops (e.g. olives), and oil crops, such as soybeans, used for purposes other than the production of vegetable oil, such as for animal feed and processed foods;
- dried pulses and beans, in dry weight, covering beans, broad beans, peas, chickpeas and lentils but excluding soybeans;
- root crops, covering mainly crops used for food and industrial use (e.g. potatoes), but excluding root crops grown principally for feed, such as fodder beets;
- fruit, covering annually sown fruit crops (e.g. strawberries) and fruit tree crops (e.g. apples);
- vegetables, covering leaf (e.g. cabbage), vine (e.g. tomatoes) and root vegetables (e.g. carrots);
- industrial crops, covering sugar crops, fibre crops and other industrial crops (e.g. tobacco);
- ornamental crops, covering crops such as flowers;
- other harvested crops, covering any other harvested crop not covered in the subcategories above;
- forage, covering annually harvested fodder crops and pasture used as livestock feed.

Crop residues

Where possible, the calculation of the soil surface N balance includes the ‘actual’ utilization or consumption of vegetation from pasture, and excludes that vegetation not utilized by livestock and remaining on pasture. Few countries regularly collect data related to pasture consumption by livestock. However, statistics are more commonly available on pasture area and pasture production, which includes both pasture vegetation consumed by livestock and that remaining in the field. For those countries with data on pasture area alone, pasture production was estimated using an assumed pasture yield figure.

For most countries, pasture consumption was estimated using the number of grazing livestock and average consumption levels per animal, or using pasture production and the consumption-production ratio.

The inclusion of crop residues in the soil surface N balance requires further research. In particular, examination is required with respect to the use of N conversion coefficients, i.e. uptake coefficients cover the N content not only in harvested cereal grains but also in other parts of the plant, which may or may not be removed from the field. Data are not provided in this entry at this stage of OECD work on the balances.

Seeds and planting materials

This category includes data on the major categories of seeds and planting materials covering:

- cereals, covering wheat, rice and coarse grains;
- oil crops, covering annually sown oil crops (e.g. soybeans), perennial oil crops (e.g. olives) and oil crops, such as soybeans, used for purposes other than the production of vegetable oil, such as for animal feed and processed foods;
- root crops, covering mainly crops used for food and industrial use (e.g. potatoes), but excluding root crops grown principally for feed, such as fodder beets;
- other crops, covering any other crops.

Biological nitrogen fixation

This category covers the planted area of legume crops that contribute to BNF, mainly pulses, soybeans, clover and alfalfa. It is the planted area and not the harvested area of legumes that is relevant as BNF occurs regardless of whether the crop is harvested or not. For example, leguminous crops are often not harvested but ploughed into the field to provide soil N.

This category also covers the land area data, i.e. arable and permanent cropland and permanent pasture, for calculating BNF by free-living micro-organisms in the soil.

Land use

This category covers agricultural land, which is subdivided into arable and permanent cropland and permanent pasture.

Coefficients to convert basic data to N content and composition vary over time and among countries. Where the availability of national N conversion coefficients is limited, the following approach is provisionally used to obtain a consistent set of coefficients:

- It is assumed that N coefficients remained unchanged in the period 1985–1997, in the absence of time series data, except for the Netherlands (annual coefficients are available) and Hungary (the coefficients are increased by 20 percent for dry years).
- While national coefficients are used where possible, coefficients for a ‘comparable’ country are used in the absence of national coefficients.

Fertilizers

This category provides the N composition coefficients to convert quantities of inorganic and organic fertilizers. From its definition (expressed in N contents, not in weight of fertilizer), nitrogenous inorganic fertilizer has a fixed N conversion coefficient of 1 000 kg/tonne. Livestock manure is not included in this category.

Livestock manure production

This category provides the coefficients to convert livestock numbers into N composition in annual manure production. However, regarding these coefficients:

- In terms of the level of disaggregation, the set of N conversion coefficients correspond as closely as possible to the data for livestock numbers.
- The coefficients take into account the slaughtering of animals in a given year.

Manure withdrawals, stocks and imports

This category provides N composition coefficients for manure withdrawals (including manure exports), changes in stocks and imports.

Harvested crops and forage

This category provides the N uptake coefficients for converting the production of harvested crops and forage into quantities of N uptake from the field. However, regarding these coefficients:

- In terms of the level of disaggregation, the set of N conversion coefficients correspond as closely as possible to the data for crop and forage production.
- Where coefficients are not available for certain crops, N coefficients that are available for similar crops are used provisionally (e.g. applying the coefficient for barley to oats).
- As N uptake includes the N content in crop residues, which remain in the field, further methodological work is required to consider this aspect properly.

Seeds and planting materials

This category provides coefficients for converting the quantities of seeds and planting materials into their N composition. Coefficients in this group are not the same as those for crops, which do not concern N composition but uptake (including uptake for by-products, such as stems and leaves).

Biological nitrogen fixation

This category provides coefficients for calculating the BNF from the planted area of leguminous crops and BNF by soil micro-organisms on all agricultural land.

Atmospheric deposition

This category provides the coefficients for calculating atmospheric deposition of N on all agricultural land.

Denitrification

The denitrification process on agricultural land is important for Japan and the Korean Peninsula, where rice production is dominant in the agricultural systems. This process is the release of mineralized nitrogen as gaseous nitrogen (N_2), which is deemed to be harmless to the environment as it is a major component of the atmosphere.

Quantity of nitrogen

This category provides the total N content of the inputs and outputs in the soil surface balance in terms of tonnes of N. The N content data in these tables are derived basically from the multiplication of the basic data (fertilizers/headage/crops) by the N coefficients.

The calculation of the soil surface N balance is:

- N input (tonnes N) = fertilizers + net input of livestock manure + other nitrogen inputs (seeds and planting materials, BNF and atmospheric deposition);
- N output (tonnes N) = total harvested crops + total forage;
- N balance (tonnes N) = N outputs - N inputs;
- N balance per hectare of agricultural land (kg/ha) = N balance (tonnes N) / total area of agricultural land (ha).

Results

The methodology developed by the OECD (OECD, 2001b) has been converted to a software and database program. The database includes data from all OECD countries for the period 1985–1998. The user can select the data required and calculate the nutrient balances.

Discussion

This case concerns mainly surpluses, which makes it different from other cases that are more typical in Africa. The data needs for the nutrient-balance model are high, which makes a well-functioning statistical office necessary. This may not be a problem for developed countries, but data availability is usually much lower for developing countries.

On the output side, OUT3 (leaching), OUT4 (gaseous losses) and OUT5 (erosion) are not included, which makes the figures in the balance strongly positive. For gaseous losses, denitrification is taken into account, but N_2O and NH_3 losses from animals, volatilization and burning are not included. On the other hand, sewage sludge and seed and planting material are included.

Soil nutrient audits for China

Sheldrick, Syers and Lingard (2002) have developed a model of the various input and output components of the nutrient cycles of N, P and K that allows national-level nutrient audits and balances to be carried out quickly and with sufficient accuracy to give meaningful results. Sheldrick, Syers and Lingard (2003a) have used this model to calculate nutrient output and input relationships, nutrient balances and nutrient depletion rates between 1961 and 1997.

Methodology

Conceptually, the model is a mass balance in which nutrients exported in crops and livestock are compared with nutrients imported into the soil. It considers the following outputs: arable crops, arable crop residues, animal products and livestock excreta. Inputs are: mineral fertilizers, crop residues, manure, animal feeds, non-livestock waste, BNF and atmospheric deposition. Obtained from FAOSTAT databases, the input information included annual crop production for both the arable and livestock sectors, fertilizers, land use and population.

The model defines nutrient efficiency as the percentage of nutrient input that is recovered as nutrient output in the crop. A nutrient balance is achieved when nutrient output no longer increases with increasing nutrient input. The study estimated nutrient efficiency using input and output data from the model. Based on nutrient audits for 197 countries for 1996, the nutrient efficiency for China for N, P and K was set at 50, 40 and 80 percent, respectively.

Of the crop residues, it was estimated that 40 percent was returned, 25 percent was consumed as animal fodder and 35 percent went to other uses or was lost from the soil nutrient cycle. N fixation was estimated at 65 percent of the total N uptake for pulses and groundnut and 50 percent for soybean. For green manure, 0.6 percent of the total N input was estimated. N fixation by Azolla in paddy rice was neglected. Atmospheric deposition was considered only for N and was set at 20 kg/ha/year. Non-livestock waste was estimated as function of population: 1 000 kg N, 250 kg P and 250 kg K per 1 000 people.

The nutrient audit model contains a detailed submodel to estimate the quantities of livestock excreta produced and recovered as manure (Sheldrick, Syers and Lingard, 2003b). The study considered different livestock categories (cattle, pigs, sheep, goats, horses and poultry). Total numbers of live animals were multiplied by the respective coefficients for the quantity of nutrient contained in excreta per animal per year. The numbers and average weights of animal slaughtered in each country were also reflected in the coefficients used to convert livestock numbers into the quantity of nutrients in livestock excreta.

Nutrient losses such as leaching, gaseous losses and erosion are not estimated directly in the model, but calculated as the difference between nutrient inputs plus nutrients depleted from the soil, and nutrient outputs in the crop. After nutrient depletion rates have been determined from the model, the total nutrient loss can be calculated.

Results

The N balance for China was calculated between 1961 and 1997 (Figure 7). First there was an increasing depletion of N, but owing to the use of large quantities of N fertilizers, this depletion subsequently decreased and came more or less into equilibrium. For P and especially K the balances grew increasingly negative. K depletion increased from 28 kg/ha in 1961 to 62 kg/ha in 1997. Table 10 shows the nutrient input and output flows for China. From the table, it appears that K depletion is highest at 41 percent of total K inputs.

Discussion

The model can readily be used for any country and year because it uses only readily available national databases. However, the model contains several major simplifications that make the results less reliable. The coefficients for crop residue removal are the same for all crops, while, for example, crop residues of cereals are generally used more intensively than those of

FIGURE 7
Nitrogen balances for China, 1961–1997

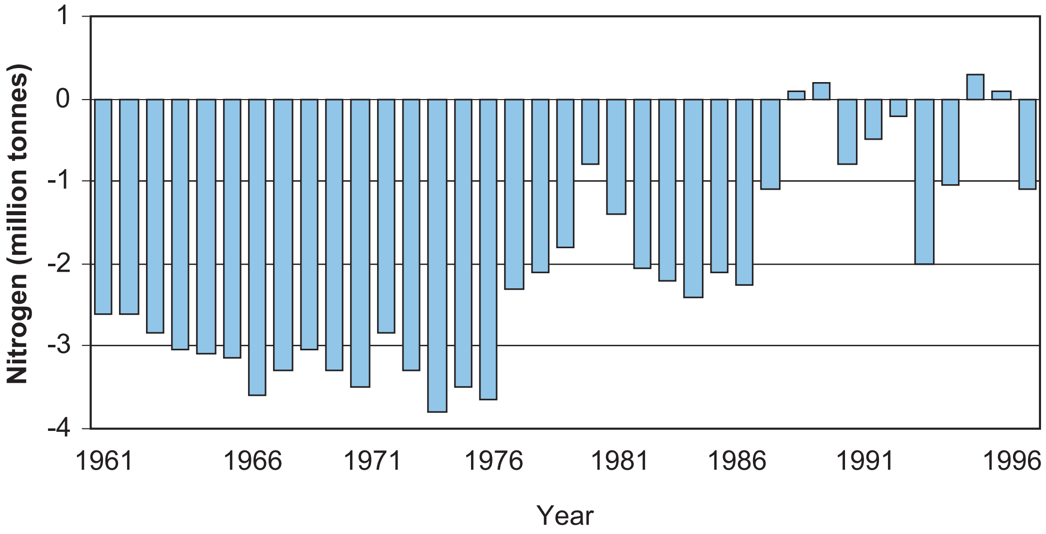


TABLE 10
Nutrient input and output flows in arable farming in China, 1997

Input flows	N		P		K	
	million tonnes	%	million tonnes	%	million tonnes	%
Fertilizer	23.3	64.7	4.1	56.8	2.8	14.1
Crop residues	2.8	7.8	0.4	5.5	5.2	26.1
Manure	5.2	14.4	1.8	25.1	3.4	17.1
N fixation	1.0	2.8				
N deposition	1.4	3.8				
Sewage	1.2	3.4	0.3	4.3	0.3	1.5
From soil	1.1	3.1	0.6	8.3	8.2	41.2
Output flows						
Arable crops	12.0	33.4	2.3	31.2	4.6	23.0
Crop residues	7.0	19.4	1.0	13.8	12.9	65.0
Losses	17.0	47.1	4.0	55.0	2.4	12.0

perennial crops. The main limitation of the model is that it depends on the assumption that nutrient efficiency is a direct function of nutrient input. Nutrient concentrations cannot change as nutrient inputs increase and the model does not allow for the effects of interactions between N, P and K. This makes the total nutrient balance less reliable, because the other losses (erosion, leaching and gaseous losses) are based indirectly on this nutrient efficiency.

Sub-Saharan Africa soil nutrient-balance study, FAO, 2003

The study was carried out as an FAO-commissioned research activity by Wageningen University, the Netherlands, in collaboration with national partners in three African countries (FAO, 2003). The purpose was to revisit and synthesize studies on soil nutrient stocks, flows and balances at macrolevel and microlevel, and to calculate them at mesolevel for a few SSA countries. The project's ultimate objective was to provide a methodology for national and subnational planners and other mesolevel stakeholders to better articulate and target scale-specific soil-fertility-enhancing measures. The mesolevel part of this study is discussed later in this chapter.

The study examined three countries: Ghana, Kenya and Mali. These countries covered major AEZs and landscapes in SSA with different farming systems. The methodology has been developed in such a way that it can be applied to all SSA countries, because the input data (continental GIS maps and FAOSTAT data) are available for each country. The calculation was performed for N, P and K based on averaged data for the period 1997–99.

Methodology

The methodology is based on Stoorvogel and Smaling (1990), with five inflows and five outflows, but has been updated and made spatially explicit. The data set on LUSs was a unique data set; only FAOSTAT data is now available, which is on a country and crop basis. This made it necessary to create a new approach based on a land use map. As land use is the main driver of the nutrient flows and balance, it was chosen to form the basis for the methodology. A procedure was developed to create a land use map based on suitabilities and showing the most likely crop distribution. This grid map with a cell size of 1 km was combined with other spatial data needed for the nutrient-balance calculation.

The methodology for land use mapping is based on three key steps:

1. Identify land units with similar topography, climate and soil conditions.
2. Match properties of the land units with crop requirements.
3. Disaggregate harvested areas from FAOSTAT over the land units.

For the creation of the land use maps the following input data were used:

- Digital Elevation Model GTOPO30 (USGS, 1998);
- FAO soil map of the world (FAO/UNESCO, 1997);
- International Institute of Applied Systems Analysis database on global climate (Leemans and Cramer, 1991);
- Global Agro-Ecological Zones (FAO and IIASA, 2000);
- Land cover map with the "seasonal land cover region" legend (USGS, University of Nebraska-Lincoln and European Commission's Joint Research Centre, 2000).

IN1: Mineral fertilizer

The input of mineral fertilizer was calculated per crop. A fraction of the total fertilizer consumption per nutrient was given to each crop (total is one). The factors were based on data of the fertilizer use per crop (IFA/IFDC/FAO, 2000). These data were not available for every country. For Ghana and Mali, this study used data from surrounding countries within the same AEZ. The FAOSTAT database yielded the figures for total fertilizer consumption per country.

IN2: Organic inputs

Livestock density maps were available for the major livestock classes, i.e. cattle, small ruminants and poultry. FAO and the environmental research group of Oxford Limited developed the cattle and small ruminant maps (FAO, 2000). The poultry density map was based on the rural population of SSA (FAO, 2001). The number of poultry was presumed to have the same spatial distribution as the rural population. The livestock densities were multiplied by the excretion per animal per year and the nutrient content of the manure. This generated the total amount of nutrients produced per livestock class.

The calculation procedure per grid cell was:

IN2 = livestock density × factor manure × factor management (during grazing) + livestock density aggregated × factor manure × factor management (application from bomas etc.)

where:

- livestock density: in kilograms per square kilometre, derived from livestock atlas;
- factor manure: excretion and nutrient content factor;
- factor management: crop and country dependent factor (from literature, experts), indicates time of grazing, manner of application and losses.

This calculation was performed for each livestock group (cattle, small ruminants and poultry) and the values summed.

IN3: Atmospheric deposition

Nutrient input by deposition consists of two parts: wet deposition related to rainfall; and dry deposition related to Harmattan dust. Factors for nutrient contents were calculated based on literature. A map with Harmattan dust deposition values was created by interpolation, based on several literature sources and wind-stream patterns. The amount of dust was derived from this map, whereas the amount of precipitation was derived from the IIASA rainfall map (Leemans and Cramer, 1991).

IN4: N fixation

Input by BNF consists of different parts, i.e.: symbiotic N fixation by leguminous crops, non-symbiotic N fixation and N-fixing trees. From the literature (Giller, 2001; Danso, 1992; Giller and Wilson, 1991; Hartemink, 2001), the percentages of total N uptake through symbiotic N fixation were:

- groundnut – 65 percent;
- soybean – 67 percent;
- pulses – 55 percent;
- sugar cane – 17 percent.

For wetland rice, cyanobacteria fix N, and this study used a value of 15 kg N/ha per year. This value is somewhat lower than most experiments reveal, but the effect of the cyanobacteria is overestimated and it does not occur in all fields. This N fixation occurs only in wetland rice, but in Africa more than 50 percent of the rice area is under upland rice. However, FAOSTAT does not differentiate between wetland and upland rice. Therefore, the amount of N fixation by cyanobacteria was multiplied by a factor for wetland rice. Ghana has 15 percent wetland rice, Kenya 25 percent and Mali 95 percent (Nyanteng, 1986). Not much literature is available for non-symbiotic N fixation and N-fixing trees. This input was estimated on the basis of the amount of rainfall using the following equation (N fixed is expressed in kilograms of N per hectare, and rainfall in millimetres per year):

$$\text{N fixed} = 0.5 + 0.1 \times \sqrt{\text{rainfall}}$$

IN5: Sedimentation

This flow consists of two parts: input of nutrients by irrigation water; and input of sediment as a result of erosion. FAO and the University of Kassel, Germany, have developed a worldwide map of irrigation areas (Döll and Siebert, 2000). The nutrient input was calculated by combining this map with the estimated amount of irrigation water (Stoorvogel and Smaling, 1990), set at 300 mm/ha/year, and the nutrient content of irrigation water (N: 3.3 mg/litre, P: 0.43 mg/litre and K: 1.4 mg/litre). The input by sedimentation was calculated by the "LandscApe ProcesS modelling at mUltidimensions and Scales" (LAPSUS) model, which also provided a feedback between IN5 and OUT5. The model output was the net sedimentation in metres. It was possible to convert this value into nutrient input by combining it with bulk density and nutrient content.

OUT1: Crop products

This study calculated the output of nutrients by crop products by multiplying yield by the nutrient content of the crops. FAO statistics (FAOSTAT) provided data on harvested area, production and, hence, yield for each country.

OUT2: Crop residues

This study calculated the output of nutrients by nutrients in crop residues by multiplying yield with nutrient content of the crop residues and a removal factor. The latter is crop and country specific, and it is based on scarce literature and expert knowledge. The removal factor reflects the type of management. Removal factors for central Kenya, with a high population density and many animals, are higher than those for southern Ghana, where livestock are relatively unimportant. A special form of residue removal is 'burning'. It is difficult to determine the extent of burning at this macrolevel. Therefore, burning was considered solely for cotton, because farmers normally burn these residues in order to prevent pests and diseases. All N is lost by volatilization and an estimated 50 percent of all K is lost directly through leaching.

OUT3: Leaching

Leaching can be an important outflow for N and K. De Willigen (2000) developed a regression model to estimate the amount of leached N. This model is based on an extensive literature search and is valid for a wide range of soils and climates. A new regression model for K leaching was developed, based on the same data set:

$$\text{N leaching} = (0.0463 + 0.0037 \times (P / (\mathrm{C} \times L))) \times (F + D \times NOM - U)$$
$$\text{K leaching} = -6.87 + 0.0117 \times P + 0.173 \times F - 0.265 \times CEC$$

where:

P = annual precipitation (mm);
C = clay (percent);
L = layer thickness (m) = rooting depth, derived from FAO (FAO, 1998);
F = mineral and organic fertilizer nitrogen (kg N/ha);
D = decomposition rate (= 1.6 percent per year);
NOM = amount of N in soil organic matter (kg N/ha);
U = uptake by crop (kg N/ha);
CEC = cation exchange capacity (cmol/kg).

The N-leaching regression model is based on 43 different measurements, where 67 percent of the variance is accounted for (De Willigen, 2000). The equation was edited slightly for perennial crops by multiplying the amount of N in soil organic matter by 0.5. This prevented overestimation of N leaching, because perennials can take up N throughout the year. The K-leaching regression model is based on 33 representative experiments and has an R^2 value of 0.45.

OUT4: Gaseous losses

This study developed a regression model to estimate gaseous nitrogen losses. The equation consisted of two parts: one regression model for the N_2O and NO_x losses through denitrification, and a direct loss factor for volatilization of NH_3. The equations were based on literature data for tropical environments. These were derived from a larger data set compiled for a recent study to estimate global gaseous emissions of NH_3, NO and N_2O from agricultural land (IFA/FAO, 2001). The N_2O regression model was based on a data set of 80 experiments and had an R^2 value of 0.45. The NO_x regression model was based on 36 different measurements and had an R^2 value of 0.91. For NH_3 emissions, 73 measurements were available. Of all fertilizer N applied, 11.3 percent is lost, with a standard deviation of 6.2 percent.

$$\text{OUT4} = (0.025 + 0.000855 \times P + 0.01725 \times F + 0.117 \times O) + 0.113 \times F$$

where:

P = annual precipitation (mm);
F = mineral and organic fertilizer nitrogen (kg N/ha);
O = organic carbon content (percent).

OUT5: Erosion

This study used the LAPSUS model to estimate erosion (Schoorl, Sonneveld and Veldkamp, 2000; Schoorl, Veldkamp and Bouma, 2002). This model simulates the amount of erosion and sedimentation at landscape scale. This method has several advantages: quantitative data is generated, erosion is considered, and sedimentation is taken into account. Main input parameters for the grid-based LAPSUS model are topographical potentials (slope gradients) from a DEM and the evaluation of the rainfall surplus that will generate the overland flow.

The study used the following input data:

- DEM, with a resolution of 1 km (USGS, 1998);
- land cover map (USGS, University of Nebraska-Lincoln and European Commission’s Joint Research Centre, 2000);
- rainfall map (Leemans and Cramer, 1991);
- soil erodibility (K-factor), derived from soil map of the world (FAO/UNESCO, 1997);
- soil depth, derived from soil map of the world (FAO/UNESCO, 1997).

The outcome of the model is a net erosion-sedimentation map with units in metres, convertible to tonnes per hectare. It is possible to calculate the loss or gain of nutrients by multiplying soil erosion by the soil nutrient contents and an enrichment factor. Based on literature, the study used the following enrichment factors: 2.3 for N, 2.8 for P, and 3.2 for K (FAO, 1984; FAO, 1986; Khisa *et al.*, 2002). It is possible to derive the nutrient content of the soil from the soil map. As a result of erosion, the rooting depth zone is extended, which means that new nutrients come within reach of plant roots. This study assumed that 25 percent of P and K, which is lost because of erosion, was gained at the rooting zone through this process.

Fallow

The amount of fallow land was calculated by subtracting the total sum of harvested areas from the total arable land. IN1 and OUT1 are not relevant for fallow. IN2 and OUT2 are related, as they comprise grazing animals and the same defecating animals. It is not known whether IN2 should be larger or smaller than OUT2. Not all manure is left on the field (only about 57 percent), but, on the other hand, a lot of animal feedstuff is obtained from sources other than crop residues, and from roadside grazing. Hence, for fallow land, the amount of nutrient input by manure (IN2) was presumed to be equal to the amount lost by grazing (OUT2). All other nutrient flows can be treated equally as for other crops.

Calculation of soil nutrient stocks

The World Inventory of Soil Emission potentials (WISE) database, developed by the International Soil Reference and Information Centre (ISRIC) was the source of all soil data for the macrolevel (Batjes, 2002). The WISE database consists of a set of homogenized worldwide data of 4 382 geo-referenced soil profiles, classified according to the FAO-UNESCO original legend (1974) and the revised legend (1988). This database yielded the soil profiles for Africa: 1 799 different soil profiles, describing 81 different soil units.

This study calculated the following soil properties for each soil unit: clay, pH, organic carbon, total N, exchangeable K, CEC, available P and bulk density. Soil depth and erodibility are not parameters in the WISE database. These were estimated for each soil unit because they are necessary for the erosion-sedimentation model. The WISE database describes soil properties per horizon, but this study used only one value per soil unit. The horizon data were converted to one value per soil profile.

In order to calculate the loss of P and K by erosion, it was necessary to recalculate the values to obtain values as percentages of the total soil mass. For exchangeable K, this is relatively easy, using the bulk density and the atomic mass of 39.1. For P, no direct relation exists between the total amount of P and the available amount of P, as derived from the WISE database. Different analytical methods exist to determine the amount of available P and each has a different relation with the total amount of P in the soil. According to the WISE database, 83 percent of all analyses were performed according to the P-Olsen method. The Bray method was used for 6 percent and the Truong method for 3 percent of all analyses. The values of P-Olsen correspond with total P as follows: > 15 is high, 5–15 is medium and < 5 is low for P-Olsen, whereas for total P, > 1 000 ppm is high, 200–1 000 ppm is medium and < 200 ppm is low (Landon, 1991). The following regression equation was developed to relate available P (P_a) to total P:

$$P_{total} = 13 \times P_a^{1.5}$$

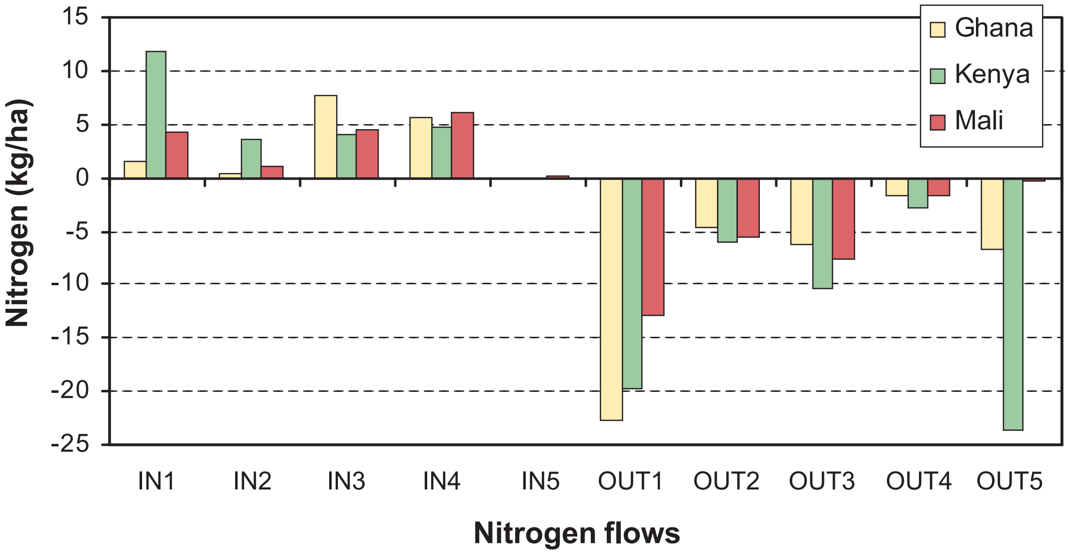
Results

Table 11
Total nutrient balances

	N	P	K
		(kg/ha)	
Ghana	-27	-4	-21
Kenya	-38	0	-23
Mali	-12	-3	-15

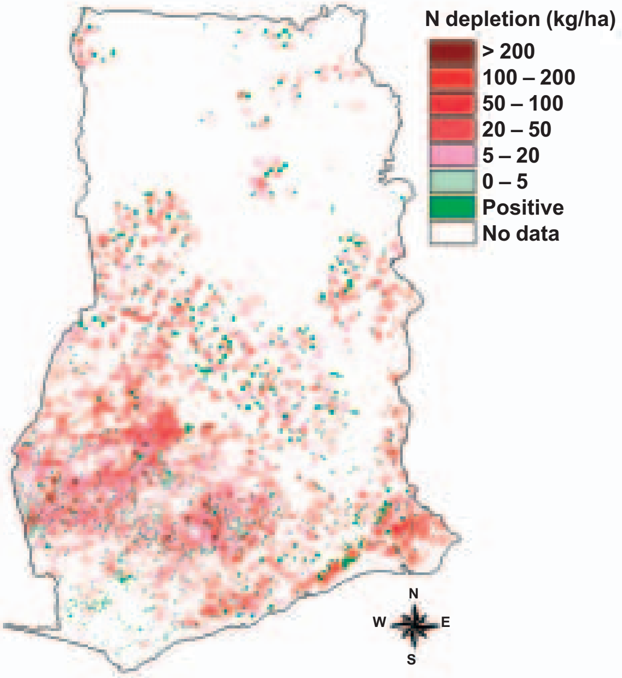
Table 11 presents the total nutrient balance for the three countries. Figure 8 highlights the differences in the nutrient flows between the countries, and shows that erosion is the main cause of the negative nutrient balance for Kenya. The results from the calculation can be linked to the original land use map, which makes it possible to present the results

FIGURE 8
Overall nitrogen flows for Ghana, Kenya and Mali



spatially (Figure 9). Linking the database system with a GIS makes it easy to analyse results per crop, nutrient flow and region.

FIGURE 9
Nitrogen balance per 1-km grid cell for Ghana



Discussion

The macrolevel calculation procedure used in this study has undergone a number of important methodological improvements compared with the original continental study by Stoorvogel and Smaling.

First, the methodology was spatially explicit. This made it possible to take the spatial variation of soils and climate into account. It also provided the possibility to indicate areas with high and low nutrient depletion within the country. The procedures for calculating the nutrient flows also underwent significant improvement (Table 12). Finally, the soil nutrient stocks were quantified for each soil unit instead of the three discrete, soil fertility classes based on FAO soil classification orders.

TABLE 12
Improvements in calculation procedure compared with the 1990 study

Flow	Methodological improvements
IN1	Fertilizer use data per crop (IFA/IFDC/FAO, 1999) available
IN2	Livestock density maps and differentiation between cattle, small ruminants and poultry included
IN3	Harmattan deposition map and more literature values available
IN4	N fixation percentages based on much more literature
IN5	Feedback between erosion-sedimentation from LAPSUS model introduced
OUT1	Comparable with the 1990 study
OUT2	Comparable with the 1990 study
OUT3	New leaching models, based on much more data, especially for N (De Willigen, 2000)
OUT4	New regression model, based on much more data from IFA/FAO (2001)
OUT5	Erosion simulated with a dynamic landscape model LAPSUS (Schoorl, Veldkamp & Bouma, 2002)

MESOLEVEL

Soil nutrient-balance study Kisii District, Kenya

After the continental nutrient-balance study of land use systems in SSA (Stoorvogel and Smaling, 1990), scale-inherent simplifications were inevitable (Stoorvogel, Smaling and Janssen, 1993). This led to a similar exercise for a well-inventoried smaller area, the Kisii District in southwest Kenya (Smaling, Stoorvogel and Windmeijer, 1993). This area of 2 200 km^2 at altitudes of 1 500–2 200 m had about 1.5 million inhabitants in 1990. The district has a high agricultural potential, but the growing population causes overexploitation of the land. Primary data were available on: climate; landforms; soils; land use; use of mineral fertilizer and farmyard manure; crop yields, residues and their nutrient content.

The district was subdivided into two temperature zones and seven LUTs. They included: extensive grazing in bushland, intensive grazing on improved pastures, tea, pyrethrum, coffee, banana, sugar cane, maize and beans (as monocrops or intercropped), sweet potato and fallow. Five rainfall zones were distinguished, with annual precipitation of 1 350–2 050 mm, and 20 soil units were found, mainly formed on volcanic rocks. This resulted in 50 LWCs and, combined with the LUTs, in a total of 107 LUSs.

Methodology

The nutrient balance with five inflows (IN1-IN5) and five outflows (OUT1-OUT5), according to Stoorvogel and Smaling (1990), was used for the calculation.

IN1

Mineral fertilizer input was based on fertilizer use data from 1980. These had to be multiplied by 2.5 for N, 2.0 for P and 3.0 for K, because fertilizer consumption in Kenya had increased considerably. Tea received most N fertilizer, and P fertilizer was applied mainly to maize.

IN2

Survey data for manure application were available. The nutrient contents of the manure were set at 1.3 percent for N, 0.5 percent for P and 1.6 percent for K, based on dry matter. Most manure was applied to coffee and bananas, and came mainly from paddocks and stables.

IN3

Atmospheric deposition was determined using the regression equations from Stoorvogel and Smaling (1990). The nutrient input was linked with the square root of the mean annual precipitation. The regression coefficients for N, P and K were 0.140, 0.023 and 0.092, respectively.

IN4

BNF was the sum of non-symbiotic N fixation and the contribution of beans, the only leguminous species in the study area. Symbiotic N fixation was set at 50 percent of the total N uptake. Non-symbiotic N fixation was determined using the regression equation of Stoorvogel and Smaling (1990):

$$\text{IN4} = 2 + (P - 1\,350) \times 0.005$$

IN5

Sedimentation was not relevant in the study area.

OUT1

Production statistics were available and were multiplied by the nutrient content of the crops. This generated the export of nutrients with harvested products. Insufficient information was available to take differences in nutrient use efficiency into account.

OUT2

The export of nutrient with crop residues was calculated by multiplying the amount of residues by the nutrient contents and a removal factor.

OUT3

Leaching of N and K were determined with a transfer function (based on literature). N leaching was calculated as a percentage of the sum of mineral N in the soil (N_{min}) and N applied by mineral and organic fertilizer. The percentages were based on rainfall and clay content (Table 13).

$$N_{min} = 20 \times N_{tot} \times M$$

where:

N_{tot} = total N content of the soil of the upper 20 cm,
M = mineralization rate (2.5 or 3.0 percent).

K leaching was calculated in a similar way with the percentages of Table 13 multiplied by the sum of exchangeable K (in kilograms per hectare) and mineral and organic fertilizer K.

Table 13
N and K leaching percentages for different rainfall and clay content

Clay content (%)	1 350		1 500		1 700		1 900		2 050	
	N	K	N	K	N	K	N	K	N	K
< 35	25	0.80	29	0.85	32.5	0.90	36	0.95	40	1
35-55	20	0.65	22.5	0.70	25	0.75	27.5	0.80	30	0.85
> 55	15	0.50	16.5	0.55	17.5	0.60	18.5	0.65	20	0.70

OUT4

For gaseous nitrogen losses, only denitrification was taken into account. A regression function based on an extensive literature research was developed:

$$\text{OUT4} = (-9.4 + 0.13 \times C + 0.01 \times P) \times (N_{min} + N_{fert})$$

where:

C = clay content (percent);
P = mean annual precipitation (mm/year);
N_{min} = mineral soil N (kg/ha);
N_{fert} = mineral and organic fertilizer N.

OUT5

Erosion was calculated using the USLE. Annual soil loss per hectare was estimated as a function of rainfall erosivity (*R*), soil erodibility (*K*), slope gradient (*S*), slope length (*L*), land cover (*C*) and land management (*P*). The *R* factor was set at 0.25 for the entire district. The *K* factor was derived from soil texture, organic matter content and permeability. The *S* and *L* factors were determined with:

$S = (0.43 + 0.30 \times s = 0.043 \times s^2)/6.613$
$L = (d/22.13)^{0.5}$

where:

s = slope gradient (percent);
d = slope length (m), set at a fixed value of 100 m.

An average *C* factor was estimated for each LUT.

The *P* factor was related with the slope (s): $P = 0.2 + 0.03 \times s$

The soil loss ($R \times K \times S \times L \times C \times P$) was multiplied by the nutrient content of the soil and an enrichment factor of 1.5 to obtain the export of nutrients by erosion. For P and K, the net loss was multiplied by 0.75 to compensate for soil formation at the root base.

For year-round fallow, equilibrium conditions were assumed, i.e. IN – OUT = 0.

Results

The total nutrient balance, the sum of the four inflows minus the sum of the five outflows, for the entire district was -112 kg/ha for N, -3 kg/ha for P and -70 kg/ha for K. The removal of harvested products (OUT1) and erosion (OUT5) were the strongest negative contributors and, for N, also leaching (OUT3). Table 14 shows the nutrient balance for each LUT component. Losses were highest under pyrethrum and, to a lesser extent, sugar cane and maize.

Discussion

This study was based on the methodology of Stoorvogel and Smaling (1990), but it was possible to calculate several flows in more detail as results of the smaller study area. For IN1, IN2, OUT1 and OUT2, it was possible to use local data instead of estimates or national averages. At this

TABLE 14
Nutrient balance of the different land use type components

LUT component	Area	N	P	K
	(ha)	(kg/ha/year)		
Fallow (year round)	8 800	0	0	0
Extensive grazing	1 800	-43	-1	-9
Continuous pasture	29 200	-98	-6	-49
Tea	19 600	-67	6	-30
Pyrethrum	17 800	-147	-24	-96
Coffee	16 500	-82	0	-34
Banana	2 900	-87	-5	-48
Sugar cane	1 500	-129	-10	-91
Maize (season 1)	13 400	-105	2	-83
Beans (season 1)	1 900	-73	-6	-55
Maize + beans (season 1)	42 800	-83	11	-63
Sweet potato	1 600	-75	-6	-51
Maize (season 2)	900	-102	-1	-80
Beans (season 2)	13 800	-75	-13	-58
Maize + beans (season 2)	9 300	-78	4	-65
Fallow (seasonal)	35 600	-53	-7	-29
Mean	157 700	-112	-3	-70

scale, it was also possible to calculate erosion (OUT5) using the USLE instead of estimates. However, the other flows were still based on transfer functions, which are not area specific.

Soil nutrient-balance study, southern Mali

Nutrient balances were calculated and evaluated economically for southern Mali (Van der Pol, 1992; Van der Pol and Traore, 1993). The study concerned cropping systems in southern Mali, where cotton, sorghum and millet are the main crops. With the withdrawal of fertilizer subsidies, the amount of fertilizer per hectare decreased and production increases were only attributable to expansion of the cotton area. Such a development increases the risk of land degradation as a result of nutrient depletion.

Methodology

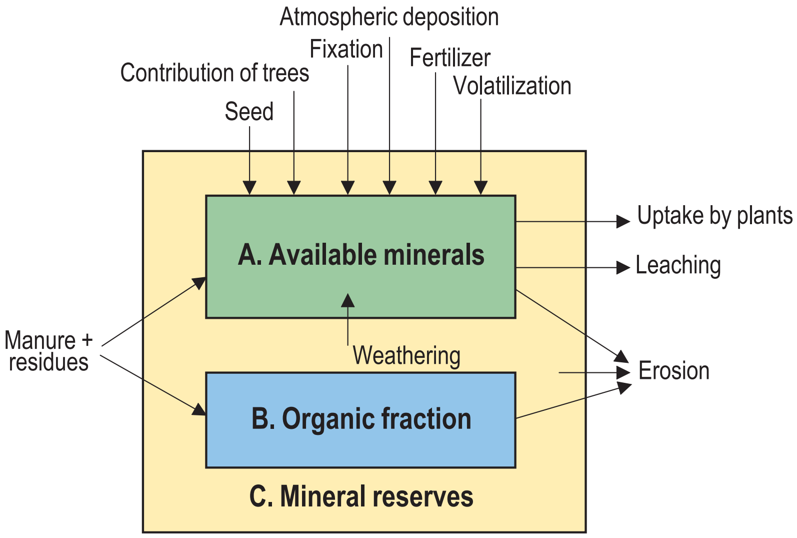
The nutrient balance for the region of southern Mali is built up from balances for the various cropping systems. Literature data were combined with locally collected production statistics. The study followed the nutrient-balance calculation approach as described by Pieri (1989) and Frissel (1978).

The nutrient elements in the soil were classified into three pools:

- A: mineral elements available to plants;
- B: elements associated with soil organic matter;
- C: mineral reserves in the soil.

Figure 10 represents the flow of nutrients in and out of the system and between these pools.

Figure 10
Nutrient flows in and out the system



Source: after Van der Pol, 1992.

In order to restrict the analysis to long-term dynamics, elements in Pool A and Pool B were considered together as nutrients. The combined size of both pools determines the fertility of a soil to a large extent. Nutrient depletion is associated strongly with a gradual decline of the organic matter content in the soil. The quantities of nutrients being depleted each year were used to estimate the rate of this decline.

On the other hand, elements in Pool C, the mineral reserve, were not considered as nutrients. On a time scale relevant to soil formation processes, an equilibrium may develop between mineral reserves and available and organic nutrients. However, the rates of change of these latter pools are too great to attain such a situation under the influence of human activities. Thus, elements were assumed to become available by transformation and dissolution of soil minerals at a constant rate, i.e. the rate of weathering.

Processes affecting the nutrient pool

In the approach used in this study, the following processes affect the nutrient pool:

- Outputs of nutrients:
  - export in cropped products;
  - losses by leaching;
  - losses by erosion;
  - losses by volatilization/denitrification;
  - incorporation of P and K in the mineral reserve ('irreversible fixation').
- Inputs of nutrients:
  - fertilizer application;
  - organic manure application;
  - restitution of crop residues;
  - symbiotic N fixation;
  - asymbiotic N fixation;

- recycling of leached nutrients and biological fixation by trees left growing in the fields;
- atmospheric deposition by rain and dust;
- transformation and dissolution of soil minerals;
- import with seed.

The difference between outputs and inputs represents the net nutrient balance.

Acidification

Acidification of soils occurs under increasingly intensive cultivation. As this can be corrected by liming, this study considered acidification as resulting from a negative 'lime balance'. Soils acidify by leaching of K, calcium (Ca) and magnesium (Mg). The loss of these elements is part of the nutrient balance but, in addition, acidification also occurs after application of ammonium fertilizer or urea, as a result of the nitrification reactions. In the calculations on acidification, it was assumed that each kilogram of fertilizer N needed 1.75 kg of lime ($CaCO_3$) for neutralization.

Reliability margins and factors of uncertainty

The basic data for nutrient inputs and outputs were selected from literature and from production statistics. Data from literature pertained to various sites in Western Africa, but were not necessarily representative for the area of the Compagnie Malienne pour le Développement des Textiles (CMDT) in southern Mali. Taking into account the variation in rainfall, soil properties, etc., some 'intelligent guessing' was necessary.

From the data, a 'most probable value' for the study region was selected, and a range representing the 95-percent probability level. If the same statistical weight is given to all literature data, the 'most probable value' is the arithmetic mean, and the range corresponds to twice the standard deviation of the mean value. However, in reality, the variability in soil properties and rainfall, and the fact that not all literature data were based on the same number of experiments, made a subjective estimate of reliability ranges more appropriate than a purely statistical procedure.

Optimistic and pessimistic views

Three net nutrient-balance values were calculated. The first was based on the use of only 'most probable' values. This value best reflected the actual nutrient balance of the region. The second value, labelled 'optimistic', was based on the combination of low estimates for the outputs and high estimates for the inputs. The third value, labelled 'pessimistic', was based on high estimates for outputs and low estimates for inputs.

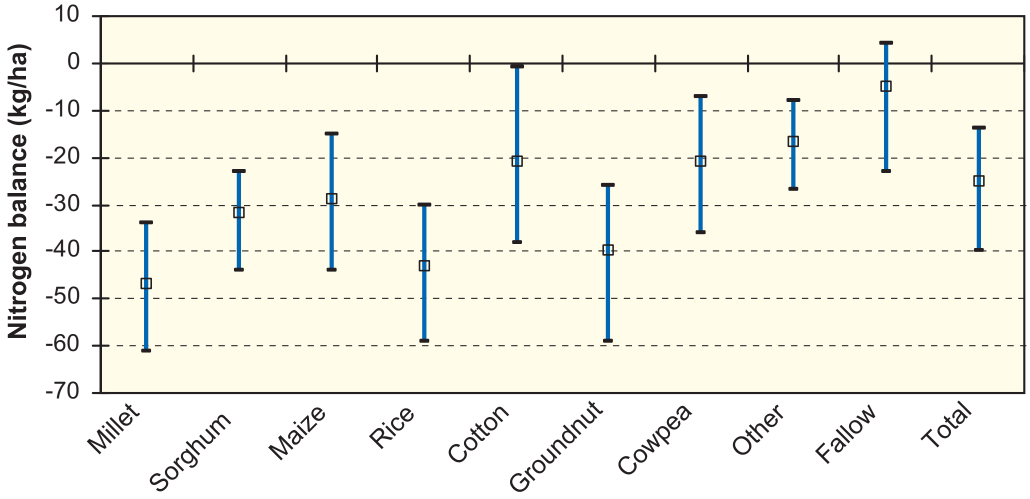
Results

Table 15 presents the total nutrient balances for southern Mali. These indicate that N and K are the most deficient elements. Most balances are negative, even with the optimistic view. The balances were also calculated per crop (Figure 11), which enables comparisons to be made between crops and conclusions to be drawn as to whether the balances offered by one crop are more favourable than those of another.

TABLE 15
Calculated nutrient balances for southern Mali

	N	P	K	Ca	Mg	Lime
	(kg/ha)					
Probable value	-25	0	-20	3	-5	-12
Optimistic	-14	2	-10	12	0	-9
Pessimistic	-40	-2	-33	-8	-10	-16

FIGURE 11
Nitrogen balance per crop with probable, optimistic and pessimistic views



Discussion

The optimistic and pessimistic views are a valuable addition because they provide more insight into the dimensions of the nutrient depletion problem and the variation and uncertainties of the outcomes. Compared to Stoorvogel and Smaling (1990), incorporation of P and K in the mineral reserve as output flow and weathering and import with seed as input flows were included. On the other hand, sedimentation and irrigation, which might be imported especially for rice, were not included.

The pool approach is more realistic than a black-box approach and gives more insight into the soil system. However, in practice it will be difficult to discriminate between the different pools. As in this study, they might have to be combined.

Nutrient-balance studies in India

Soil nutrient-balance studies in various agro-ecological regions of India that are based on broad parameters for input and output flows provide a mesolevel insight into soil fertility aspects. In the two studies reported here, one examined nutrient mining in different agroclimatic zones of Andhra Pradesh State and the other study calculated nutrient removals in Rajasthan State.

Methodology

Andhra Pradesh

Nutrient removal by various crops from soils of different agroclimatic zones of Andhra Pradesh was computed on the basis of nutrient removal per specified economic yield (Singh *et al.*, 2001). In order to proceed with the computations, district-level data on area and production for 1998–99 were used for 15 major crops. District-level fertilizer use data were used in order to calculate nutrient additions through fertilizers. From the district-level data, zone-level nutrient additions were determined by adding the data of the cluster of districts falling in the respective zone.

The share of nine major crops in fertilizer consumption was assumed as 95 percent; the remaining 5 percent was assumed to be consumed by the other crops and vegetables and fruits. Furthermore, while calculating the share of organic sources of nutrients, it was assumed that the total potential of various organic resources and their equivalent plant nutrients were distributed uniformly in the seven agroclimatic zones based on the information of gross cropped area. Finally, 10 percent of the total organic nutrient potential was considered trappable for the purpose of the computations. The nutrient balance was calculated as:

$$\text{Nutrient balance} = [\{(A \times 0.95) \times EF\} + (B \times 0.10)] - [TR]$$

where:

A = total fertilizer nutrients used in the zone for all the crops;

EF = fertilizer use efficiency factor (N = 0.45; P = 0.25; K = 0.70);

B = nutrient addition through organic manures;

TR = total nutrients removed by crops.

Rajasthan

Nutrient removals were calculated on the basis of published production figures for the major crops and averaged nutrient removal figures from several studies (Gupta, 2001). Figures for mineral fertilizer use were those of fertilizer agencies. The need was perceived for a systematic database with regard to nutrient status of soils, removal of nutrients by different crops/varieties, amount of N fixed by various legumes, and probable contribution of organic manures. The nutrient balance was calculated as:

$$\text{Nutrient balance} = [(A \times EF) + D + BNF] - [TR]$$

where:

A = total fertilizer nutrients used;

EF = fertilizer use efficiency factor (0.50);

D = N addition through rain (5 kg/ha/year);

BNF = N fixation through legumes (15 kg/ha/year);

TR = total nutrients removed by crops.

Results

For Andhra Pradesh, the overall balance for N was positive (0.207 million tonnes), while both the P and K balances were negative (-0.133 million tonnes and -0.431 million tonnes, respectively). The results varied largely between the different agroclimatic zones.

Discussion

Both studies used a simple nutrient balance with the main inputs and outputs. However, they neglected important outflows such as leaching and erosion. In addition, there is some difficulty in comparing these studies with others as the outcomes are in tonnes rather than kilograms per hectare. However, the results do show the relative differences between the zones, which can form a basis for future strategies, e.g. for increased fertilizer use.

Sub-Saharan Africa soil nutrient-balance study, FAO, 2003

The overall purpose of this study and its macrolevel aspect is reviewed above. The particular hypothesis in this study is that the mesolevel offers a suitable entry point for policy-makers and private sector intervention, where macrolevel and microlevel are not appropriate for policy-making at subnational level. Within such a mesolevel system, the commercial component may function as the engine of the farming system, allowing for intensification and expansion. This cash component can function as a driver for soil fertility management.

The study examined three farming systems with a cash crop or other market-oriented agriculture component in different AEZs: the cocoa-based farming system in Nkawie District and Wassa Amenfi District, Ghana; the tea-coffee-dairy farming system in Embu District, Kenya; and the cotton-based farming system in Koutiala Region, Mali.

Methodology

At the mesolevel, the methodology followed the calculation for the macrolevel. However, owing to the lack of spatial data of sufficiently high resolution, it was not possible to perform calculations on a spatial basis. Therefore, the nutrient balance was calculated on a tabular basis. Relations between land use and soils were established in order to compensate for the lack of spatial data.

At the mesolevel, a 1-km grid is too coarse to represent physiographic differences with sufficient accuracy. Although a land use map can be created on the basis of aerial photographs or satellite images with fast field checks, these were not available for the study areas.

The data availability for the three countries was very different; this prohibited a generic approach at mesolevel. The general procedures for each nutrient flow are described below.

IN1 Mineral fertilizer

The data on mineral fertilizer were derived from farm surveys, recommended fertilizer rates or macrolevel data, depending on the data availability in each study area. Recommended fertilizer rates are in general much higher than the actual application rates. This is because not all farmers can afford or want to apply these quantities. Therefore, the fertilizer rates were multiplied by a factor representing the ratio between the harvested area at mesolevel and the harvested area at national level in order to prevent overestimation.

IN2 Organic fertilizer

The amount of available manure was derived from the number of livestock within the study area, using excretion, nutrient content and loss factors. The application per crop was derived from farm surveys and estimates. Local nutrient content values were used where available.

IN3 Atmospheric deposition

The atmospheric deposition was derived from the macrolevel. Rainfall data from local weather stations were used; where such data were not available, they were derived from the macrolevel.

IN4 N fixation

N fixation was treated in a similar way as for the macrolevel. Where available, specific data related to N on fixation should be included, e.g. agroforestry systems with N-fixing trees.

IN5 Sedimentation

Irrigation was not relevant for the three case-study areas. Sedimentation was estimated for crops grown in river valleys, e.g. rice. The LAPSUS model was not used at the mesolevel because of the lack of spatial data.

OUT1 Crop products

Crop production data were multiplied by nutrient contents of the crops. Where available, local nutrient content factors were used as these can be significantly different from the average continental values used at the macrolevel.

OUT2 Crop residues

Crop residue removal factors were derived from farm surveys or estimated by local experts. These factors were multiplied by the production and the nutrient content factors of the crop residues.

OUT3 Leaching

The regression models used for the macrolevel were used to calculate N and K leaching.

OUT4 Gaseous losses

The regression model used for the macrolevel was used to estimate the gaseous nitrogen losses.

OUT5 Erosion

Estimates of erosion were made for each crop. These estimates took regional differences in topography and soils into account, and were based on literature and expert knowledge. Although suitable for mesolevel, the LAPSUS model was not used because of the lack of spatial data.

Results

The study compared two districts in Ghana. Nkawie District is more densely populated and has a long land use history under cocoa. Wassa Amenfi District has experienced a large increase in the cocoa area in recent decades event though the area is less suitable for cocoa.

TABLE 16
Nutrient balance for two cocoa districts, Ghana

Crops	Nkawie District				Wassa Amenfi District			
	Area	N	P	K	Area	N	P	K
	(ha)	(kg/ha)			(ha)	(kg/ha)		
Cocoa	48 493	-3.2	-0.1	-8.5	240 961	-1.5	-0.2	-9.2
Maize	11 455	-32.4	-6.3	-20.3	5 650	-23.8	-5.4	-13.5
Cassava	11 838	-68.3	-9.6	-59.0	7 700	-53.3	-7.6	-50.3
Plantain	11 725	-8.7	-0.3	-35.6	5 000	-6.2	-0.5	-35.4
Cocoyam	9 514	-50.8	-3.3	-39.9	3 000	-34.0	-1.9	-26.1
Yam	1 175	-55.0	-3.7	-42.9	1 500	-85.8	-6.0	-63.3
Rice	1 462	7.5	4.0	-9.8	2 112	10.1	5.0	-7.3
Vegetables	-	-	-	-	250	-57.8	-7.0	-29.3
Oil-palm	-	-	-	-	900	-29.2	-7.2	-54.1
Fallow	14 600	-0.6	0.9	-2.5	7 300	1.8	0.9	-3.2
Total	110 262	-18.0	-1.9	-20.3	274 373	-4.3	-0.5	-11.4

Table 16 shows the resulting nutrient balances per crop for both districts. The balances for Nkawie District are more negative than those for Wassa Amenfi District. The main reason for this difference relates to the area under cocoa, which is 58 percent for Nkawie District and 90 percent for Wassa Amenfi District. The nutrient balance for cocoa is only slightly negative, unlike most crops. In particular, cassava, yam and cocoyam have strongly negative nutrient balances.

Discussion

The study shows that a mesolevel nutrient balance can be assembled properly, provided that sufficient data are available. The mesolevel results provide information that cannot be deduced from macrolevel and microlevel studies. Mesolevel nutrient balances will have greater potential when they are made spatially explicit. In this study, not enough spatial data were available. In particular, the erosion estimates can be improved significantly using the LAPSUS model. Without the spatial component, the mesolevel approach is not very different from the previous mesolevel cases.

MICROLEVEL

NUTMON – nutrient monitoring for tropical farming systems

NUTMON (NUTrient MONitoring) is an integrated, multidisciplinary methodology that targets different actors in the process of managing natural resources in general and soil nutrients in particular. With the NUTMON methodology, farmers and researchers jointly analyse the environmental and financial sustainability of tropical farming systems. The NUTMON-toolbox (manual plus accompanying software) has been developed to integrate the assessment of nutrient stocks and flows with economic farm analyses. It has been tested and applied in diverse AEZs in close cooperation with partners from Kenya, Ethiopia, Uganda, Burkina Faso, China and Viet Nam (Vlaming *et al.*, 2001). More information and the toolbox are available at: www.nutmon.org.

Participatory research techniques, such as resource flow mapping, matrix ranking and trend analysis, are used to obtain the farmers' perspective. A quantitative analysis generates import indicators such as nutrient flows, nutrient balances, cash flows, gross margins and farm income. Both the qualitative and quantitative analyses are then used to improve or design new technologies that tackle soil fertility management problems and can help improve the financial performance of the farm.

The problem of soil fertility management has biophysical, economic and socio-cultural aspects. From a biophysical standpoint, soil fertility depletion relates to low and untimely or inefficient application of manure and fertilizer, farm management practices that lead to high losses through leaching and erosion, and to the lack of integration of livestock. From an economic standpoint, soil fertility decline relates to short-term economic considerations of farm households, insecure climate and market environment, poor property rights, limited infrastructure and risk management. Socio-cultural aspects are also important because they influence the decision-making of farmers. Farmers' perceptions, knowledge, creativity and competence are essential elements for the adoption of new technologies. Gender issues also play an important role. Female-headed households often have less access to fertilizers because of cash constraints or because extension systems and marketing organizations ignore them. In order to tackle the different problems of soil fertility decline effectively, the integration of disciplines (soil science, agronomy, animal husbandry, economy and sociology) is a prerequisite, as is the integration of formal science and farmers' knowledge.

Defined as the judicious manipulation of nutrient stocks and flows in a way that leads to satisfactory and sustained production from environmental, financial and socio-cultural standpoints, integrated nutrient management (INM) is seen as the way ahead. This represents a major shift from traditional fertilizer trials aimed at increased production towards comprehensive solutions in the field of integration of organic and inorganic fertilizers, integration of livestock, soil water conservation, agricultural policies and marketing.

Methodology

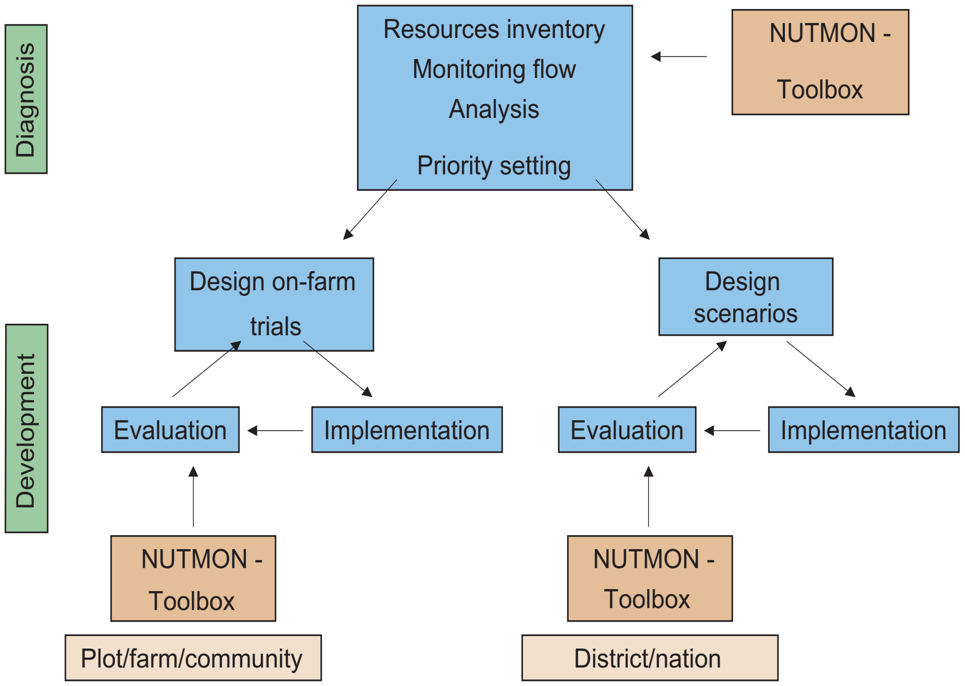
The NUTMON approach distinguishes two phases: the diagnostic phase and the development phase (Figure 12). Multidisciplinarity and integration of knowledge systems are important in both phases.

Diagnostic phase

The diagnostic phase is carried out at farm level as farm management decisions are taken at this level. The goal of the diagnostic phase is a participatory analysis of the current situation regarding soil nutrient depletion and economic performance. It entails the application of the various tools in the NUTMON-toolbox, preceded by participatory techniques, such as a participatory rural appraisal (PRA) and participatory resource flow mapping. The NUTMON-toolbox plays a central role in this phase as it quantifies the nutrient flows between soils, crops and livestock. Flows are expressed in kilograms of N, P and K (nutrient flows), but also in monetary values (financial flows). The quantified nutrient flows explain which activities within a farm are nutrient consuming and which are accumulating nutrients, and how and when nutrients flow from one activity to another. The quantified financial flows give insight into the profitability of activities (crops, livestock, fishponds and compost pits) and labour demands.

Soil sampling and analysis provides essential information concerning the current nutrient status of the soils. A variety of existing participatory tools can be used to collect and analyse the perceptions of other stakeholders concerning the current soil fertility problems. The quantitative results of the NUTMON-toolbox, combined with the often qualitative information from the other

Figure 12
Overview of the NUTMON approach and the role of the NUTMON-toolbox



stakeholders, provide a solid basis for an appropriate, thorough and participatory diagnosis. Products of this phase are: quantified nutrient flows and stocks; financial performance indicators; flow diagrams; ranking of problems and possible solutions; and historical descriptions of farm management. During the process, the perceptions and strategies of various stakeholders (farmers, researchers, extensionists) and biophysical and economic boundary conditions surface, resulting in a common understanding of the problem.

Development phase

The development phase that follows can be executed at two different scales. At farm level, a process of participatory technology development is launched with the aim of identifying and developing technologies to address the problems identified in the diagnostic phase. Based on the diagnosis, farmers prioritize technologies, which are tested on-farm. For example, negative nutrient balances caused by large outflows of erosion and leaching may call for soil and water conservation technologies. A situation where low application levels of external inputs has caused negative nutrient balances may call for changes in the marketing infrastructure to make external inputs more attractive.

The NUTMON-toolbox plays an important role in monitoring and evaluating the impact of applied technologies by providing scientific and quantitative information. Similar to the diagnostic phase, other tools and methods are applied to arrive at an impact evaluation by farmers (De Jager, Nandwa and Okoth, 1998; Vlaming, Gitari and Van Wijk, 1997). At regional level, a participatory policy development process can be launched. The results of a farm diagnosis of the major farming systems in a region are scaled up to regional level and presented to policy-makers. Policy interventions are defined in discussions between farmers, scientists and policy-makers.

In both phases, knowledge and experiences are tapped from both science-based and local knowledge systems in order to arrive at the most appropriate solutions. The process of integration of these knowledge systems results in research capacity building for farmers (learning how to conduct applied research) and researchers (increasing knowledge of farm management practices).

NUTMON-toolbox

The NUTMON-toolbox consists of four modules and two databases that together facilitate nutrient monitoring at the level of individual farmers' fields and farms as a whole.

The four modules consist of:

- a set of questionnaires that collects the required farm-specific information on management, the farm environment, the farm household, soils and climate;
- a data entry module that facilitates entry of the data from the questionnaires into the computer;
- a background processing module that stores non-specific information on crops, crop residues, animals, inputs and outputs;
- a data processing module that calculates nutrient flows, nutrient balances and economic indicators, based on the farm-specific data from the questionnaires and general data from the background database, using calculation rules and assumptions.

The two databases are:

- a background database containing non-farm-specific information on, for example, nutrient contents of crop and animal products, crop and livestock parameters, as well as calibration factors of local units of measurement;
- a farm database containing farm-specific information. One farm database contains information on a set of farms that are part of one study.

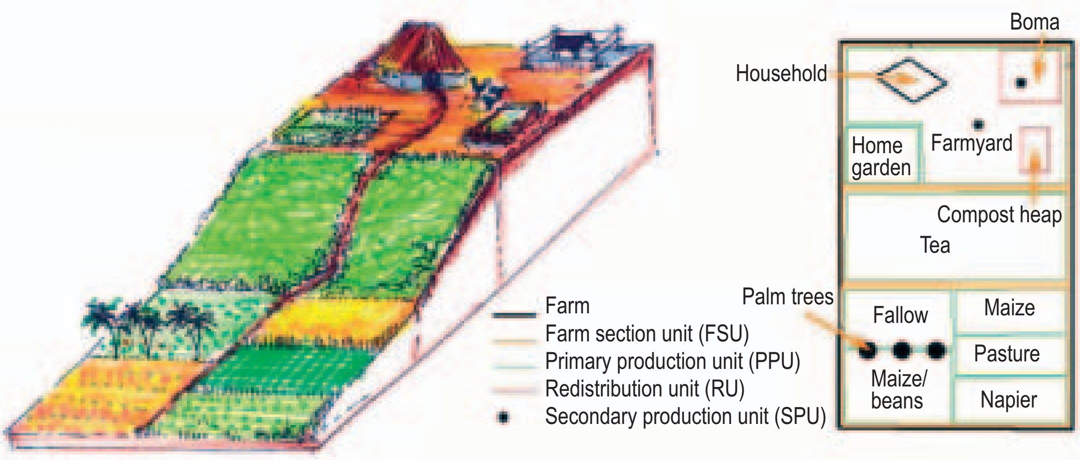
Conceptual framework

Because the complexity of farms does not usually allow for quantification of all nutrient flows and stocks, a conceptual framework has been developed. The framework simplifies reality to the extent that major nutrient flows and pools are included and minor flows and pools are neglected. The framework consists of four major components:

- farm section units (FSUs), which are continuous farm fields;
- nutrient pools, such as crops, livestock and compost pits;
- other entities that play a role in farm management (soils, climate and markets);
- nutrient and cash flows, e.g. harvested crop products, mineral fertilizer and labour.

The boundaries of the farm coincide with the physical borders. The lower boundary is the depth to which leached nutrients are assumed to be lost from the system, as defined in the leaching transfer function.

FIGURE 13
The farm concept as used in NUTMON



The farm concept (Figure 13) differentiates the farm in farm section units (FSUs), primary production units (PPUs), redistribution units (RUs) and secondary production units (SPUs). An FSU is a continuous field within the farm, which is assumed to have homogeneous soil properties, slope, flooding regime and land tenure. The FSUs are defined because soil and land characteristics determine some of the nutrient flows (e.g. leaching and erosion). A PPU is a crop activity consisting of one or various crops grown deliberately in one field within the farm. It can include annual and perennial crops, pasture or fallow. An RU is a location within the farm where nutrients are collected or accumulated and from where nutrients are redistributed, e.g. stables, corrals, fish ponds, compost pits and latrines. An SPU is defined as a group of animals of the same breed/species managed by the farmer.

Quantifying nutrient flows

Figure 14 presents the inflows and outflows that are accounted for at the farm level in NUTMON. These flows are quantified using four methods: (i) asking the farmer; (ii) using transfer functions; (iii) livestock mode; and (iv) assumptions. All nutrient flows are determined in kilograms of nutrient per hectare per year.

IN1 (mineral fertilizer) is determined by asking the farmer and combining the applied quantities with the nutrient contents from the background database.

IN2 (organic inputs) is determined by asking the farmer and combining the applied quantities with the nutrient contents from the background database.

IN3 (atmospheric deposition) is determined using three transfer functions:

N: $\text{IN3} = 0.14 \times P$

P: $\text{IN3} = 0.023 \times P$

K: $\text{IN3} = 0.092 \times P$

where P = annual precipitation (mm/year).

IN4 (BNF) consists of two parts: symbiotic and non-symbiotic N fixation. Non-symbiotic N fixation is determined using the mean annual precipitation P:

$\text{IN4} = 2 + (P - 1\,350) \times 0.005$

The symbiotic N fixation is assumed to be a crop-specific percentage of the total N uptake of leguminous species (annual or perennial). The total N uptake is defined as the sum of the amounts of N in the crop product and the crop residues.

IN5 (sedimentation) is the amount of irrigation multiplied by the nutrient content of the irrigation water.

IN6 (subsoil exploitation) is normally ignored because of the difficulties in determining this flow and its small contribution to the total nutrient balance.

OUT1 (farm products) is obtained from the questionnaires and is multiplied by the nutrient content of the crops from the background database.

OUT2 (other organic outputs) is also obtained by asking the farmer and the quantities are multiplied by the nutrient content from the background database.

OUT3 (leaching) is determined by transfer functions. For N leaching, one can choose between the 'De Willigen 2000 model' and the 'Smaling 1993 model'. The De Willigen 2000 model is based on an extensive literature review (De Willigen, 2000).

$\text{OUT3} = 21.37 + (P/C \times L) \times (0.0037 \times N_f + 0.0000601 \times O_c - 0.00362 \times N_u)$

where:

$P =$ annual precipitation (mm/year);

$C =$ clay content (percent);

$L =$ rooting depth (m);

$N_f =$ mineral fertilizer N;

$O_c =$ organic carbon content of the soil (percent);

$N_u =$ N uptake by the crop (kg/ha/year).

The Smaling 1993 model is a simple transfer function based on soil and fertilizer N (Smaling, 1993):

$\text{OUT3} = (N_s + N_f) \times (0.021 \times P - 3.9)$ $C < 35$ percent

$\text{OUT3} = (N_s + N_f) \times (0.014 \times P + 0.71)$ 35 percent $< C < 55$ percent

$\text{OUT3} = (N_s + N_f) \times (0.0071 \times P + 5.4)$ $C > 55$ percent

where:

$N_s =$ amount of mineralized N in the upper 20 cm of the soil;

$N_f =$ amount of N applied with mineral and organic fertilizers;

$P =$ annual precipitation (mm/year);

$C =$ clay content of the topsoil (percent).

For K leaching, only the Smaling 1993 model can be used:

$\text{OUT3} = (K_e + K_f) \times (0.00029 \times P + 0.41)$ $C < 35$ percent

$\text{OUT3} = (K_e + K_f) \times (0.00029 \times P + 0.26)$ 35 percent $< C < 55$ percent

$\text{OUT3} = (K_e + K_f) \times (0.00029 \times P + 0.11)$ $C > 55$ percent

where:

$K_e =$ exchangeable K (cmol/kg);

K_f = amount of K applied with mineral and organic fertilizers;
P = annual precipitation (mm/year);
C = clay content of the topsoil (percent).

OUT4 (gaseous losses) consists of two parts: gaseous N losses from the soil, and gaseous N losses related with storage of organic inputs. Gaseous N losses from the soil are calculated as a function of the clay percentage and the precipitation:

$$OUT4 = (N_s + N_f) \times (-9.4 + 0.13 \times C + 0.01 \times P)$$

where:

N_s = mineralized N in the rootable zone (kg/ha);
N_f = N applied with mineral and organic fertilizer (kg/ha);
C = clay content (percent);
P = mean annual precipitation (mm/year).

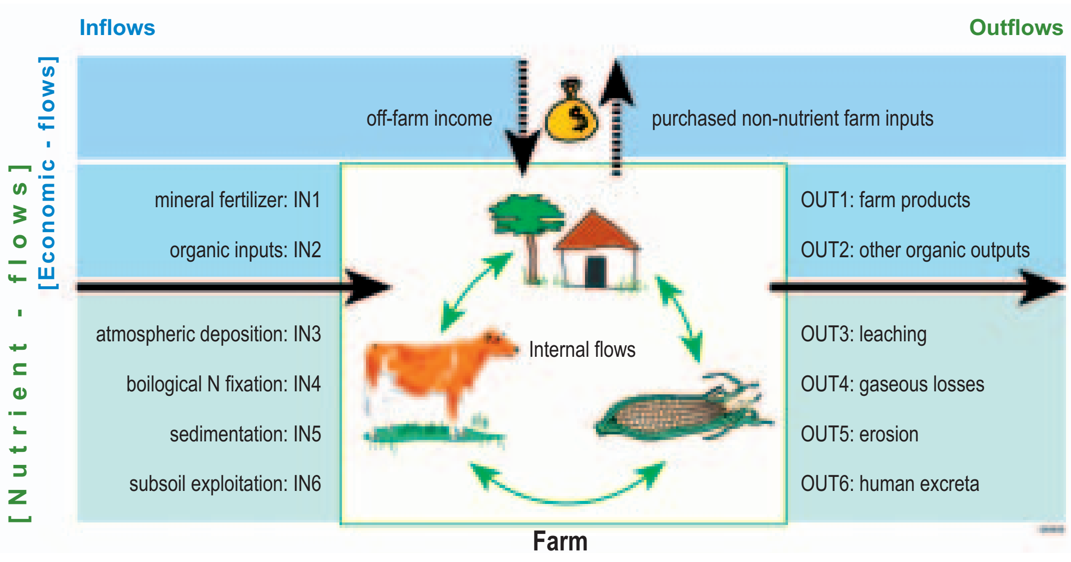
Gaseous N losses related to the storage of organic inputs (manure and compost) are calculated with a user-defined percentage based on roofs, etc.

OUT5 (erosion) is calculated using the USLE. A hypothetical soil loss per FSU is calculated based on slope, slope length, rainfall, soil characteristics and the presence of soil conservation measures. For each PPU, the hypothetical soil loss (in kilograms per hectare per year) is multiplied by a crop cover factor, the nutrient content of the soil and an enrichment factor.

OUT6 (human excreta) are calculated with a user-defined amount per consumer unit. The human excreta can be distributed into a PPU or RU or are completely lost in the case of a deep latrine.

A livestock model has been developed to estimate: (i) the amount and type of feed consumed by livestock; (ii) the amount and composition of the manure excreted by livestock; and (iii) the distribution of the excreted manure over the various units within the farm. The model can

Figure 14
Nutrient and economic flows that influence the nutrient balance and farm income



be used for all animal types, but is more elaborated for cattle. The model makes no distinction between nutrients excreted in urine and manure.

Results

The NUTMON methodology has been applied in several studies and projects and many copies of the NUTMON-toolbox have been distributed to institutes in the tropics. Descriptions of projects and results are available on the NUTMON Web site (www.nutmon.org). Results from nutrient monitoring in three districts in Kenya are described in Van den Bosch *et al.* (1998) and De Jager, Nandwa and Okoth (1998). The sustainability of low-external-input farm management systems was assessed using the NUTMON approach for a case study in Kenya in De Jager *et al.* (2001). The VARINUTS project (SC-DLO *et al.*, 2000) used the NUTMON approach to determine variations in soil fertility management in five AEZs in Embu District, Kenya.

Discussion

Although based on Stoorvogel and Smaling (1990), the NUTMON approach has been developed out completely at the farm level. This means that it can also serve as a tool for monitoring nutrient flows on farms. The methodology has been converted to a software program with databases and questionnaires. Therefore, the methodology is in widespread use in many farm-level projects. However, high data needs make the model less suitable for a rapid inventory.

Participatory nutrient management in southern Mali

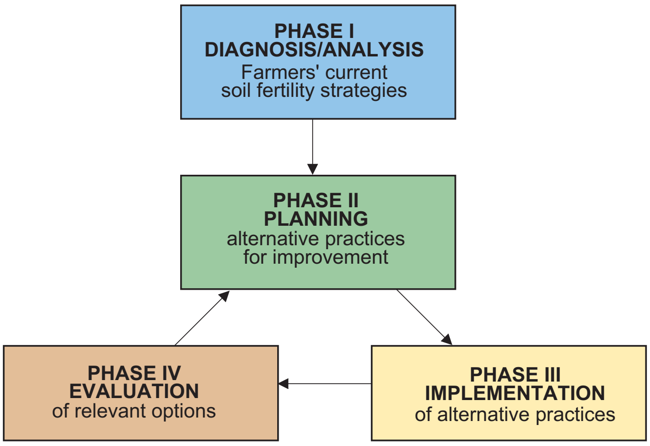
Distinct farming systems associated with different ethnic subregions characterize the agropastoral community of southern Mali. Varying reliance on livestock, inorganic fertilizers and bush fallowing account for significantly different nutrient balances. While nutrient balances are indispensable, they are methodologically complex tools. The study reviewed here outlines some of the potential difficulties arising from assumptions made about soil processes and both spatial and temporal system boundaries (Ramisch, 1999).

The study area was the village of Lanfiéla in southern Mali, an area with sandy loam soils and a relatively high annual rainfall (1 100 mm). Intensive agriculture based on cotton and draught power and large cattle herds coexist within its boundaries. The study divided the area into three groups: village, hamlet and Fulani. Village refers only to the cluster of interconnected compounds at the centre of the cultivated plain; Fulani refers to the semi-sedentary Fulani residents; and hamlet covers all non-Fulani households whose compounds are surrounded by their own cultivated fields.

Methodology

The nutrient balance was based on Stoorvogel and Smaling (1990), but combined with a new participatory approach. This methodological approach is called participatory learning and action research (PLAR) (Defoer, 2000; Defoer, 2002). It consists of four phases (Figure 15); the cycle is repeated on a crop seasonal basis and forms the heart of the long-term engagement between farmers and researchers. The PLAR approach can be compared with the farmer field school (FFS) approach. However, the FFS approach does not deal explicitly with diversity and it does not build on a long-term engagement of farming communities. The PLAR approach is based on four principles that are applicable in each of the phases:

FIGURE 15
Participatory Learning and Action Research process



Source: Defoer, 2002.

- PLAR is a community approach.
- PLAR addresses diversity.
- PLAR deals with representative test farmers.
- PLAR builds on feedback.

Two levels of investigation are distinguished: the village community or group of farmers, and the farm household. The diagnostic phase consists of eight steps:

- Introductory community meeting (community level).
- Analysis of the village land use system (group level).
- Analysis of management diversity (group level).
- Diagram of village organizations (group level).
- Selection of test farmers (group level).
- Formation of a farmer committee (group level).
- Farm resource flow map (household level).
- Concluding community meeting (community level).

One of the main elements of the diagnostic phase is the making of a resource flow map by the farmers themselves. This map depicts farm fields and other farm elements, such as kraals and compost pits (Figure 16). The resource flows between fields and other farm elements are drawn as are resources leaving or entering the farm, e.g. crop products and mineral fertilizer. The resource flow maps provide the starting point for constant monitoring and evaluation of the fields over the season.

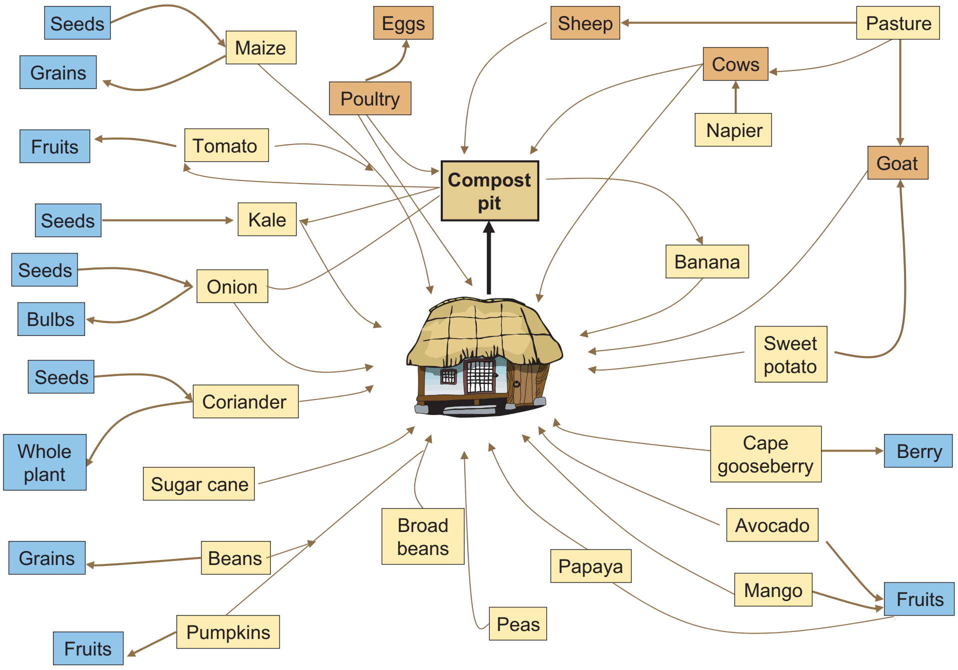
Steps in the planning phase are:

- Farmers' workshop (community level).
- Farmer exchange visit (group level).
- Planning map (household level).
- Committee's action plan (community level).
- Concluding planning meeting (community level).

In the implementation phase the farmers are assisted with:

- Farmer training sessions (group level).
- Experiment design meeting (group level).
- Demonstration of layout (group level).
- Monitoring of experiments (household level).
- Field visit (group level).
- Farmer-to-farmer training (group level).
- Managing experiment data (group level).
- Field day (community level).

FIGURE 16
Example of a resource flow map



The last phase of the PLAR process, the evaluation phase has three steps:

- Introductory evaluation meeting (community level).
- Map of implemented activities (household level).
- Evaluation of the action plan and concluding evaluation meeting (group/ community level).

The nutrient-balance model

The model determines net surpluses or deficits of nutrients by measuring and summing all of the imports and exports of resources from a given plot (Table 17). Exports that are management-influenced are all those concerning the fate of crop residues. These include whether to: (i) stock them for livestock feed or litter; (ii) compost them directly with other organic waste; or (iii) burn them in the fields (immediately after harvest or later in the season). Residues left in the fields unburnt are often grazed *in situ* by livestock, and then allowed to decompose under the influence of termites and other processes. Where relevant, the study distinguished between grazing by the household's own animals and that by animals from other farms. Grazing by one's own animals is, like stocking or composting, a transfer that potentially keeps nutrients within the same field-herd-household, while grazing by other animals exports nutrients completely outside of that system.

On the import side of the balance sheet, management-related transfers involve all the 'intentional' movements of organic matter to the fields from livestock pens or compost pits, as well as the application of inorganic fertilizers. The manure from livestock herds corralled on fields in the dry season is also a management-related input. 'Management' also influences the movement of livestock within and across the fields, determining the nutrients introduced

Table 17
Variables considered in the nutrient-balance calculations

	Exports	Imports
Management	OUT1 Harvested crop	IN1 Inorganic fertilizer
	OUT2 Crop residues	Complex (NPK + SB)
	Stocked	Urea
	Composted	IN2 Transported to field
	Grazed *in situ*	Compost
	Burnt	Household waste
	Left in fields	Pen manure
		Manure deposited by corralled animals
		Manure deposited by grazing animals
Environmental	OUT3 Leaching	IN3 Atmospheric deposition
	OUT4 Denitrification & volatilization	IN4 Biological fixation
	OUT5 Erosion	IN5 Parent material (sedimentation)

‘in passing’ by grazing animals allowed to use the field as corridors across the landscape even after the residues have been consumed. The environmental transfers are determined largely by regional climate, especially the inputs via atmospheric deposition (dust and rainfall), asymbiotic fixation, and the weathering of parent material. The exports are also driven by factors external to management, but which interact with the management transfers. For example, while largely a function of slope, soil type and rainfall, erosion is also influenced by crop cover and human management.

Mineral leaching and gaseous nitrogen losses (through volatilization and denitrification) are also a function of the quantities of nutrients applied. Owing to logistic constraints in the field, these transfers were estimated using the criteria listed in Table 18.

Table 18
Mean nutrient values retained for environmental transfers

Transfer	N	P_2O_5	K_2O
IN3 - Atmospheric deposition	5 kg/ha	1.2 kg/ha	3.5 kg/ha
IN4 - Biological fixation (symbiotic)	50% of uptake		
IN4 - Biological fixation (asymbiotic)	2 kg/ha		
IN5 - Weathering		1 kg/ha	5 kg/ha
OUT3 - Leaching			
Cotton	7 kg/ha	1 kg/ha	16 kg/ha
Legumes	15 kg/ha	1 kg/ha	16 kg/ha
Maize	6 kg/ha	1 kg/ha	16 kg/ha
Millets/sorghum	1.5 kg/ha	1 kg/ha	16 kg/ha
OUT4 - Volatilization	(Soils too acid)		
OUT4 - Denitrification	10 kg/ha + 30% applied - 10% uptake		
OUT5 - Erosion	0.76 kg/tonne sediment	0.26 kg/tonne sediment	0.46 kg/tonne sediment

TABLE 19
Sample-wide nutrient balances

	Entire sample (256 ha)	Village (n = 191)	Hamlets (n = 59)	Fulani (n = 13)
	(kg/ha)			
N	-8.2	-11.9	-4.7	23.3
P_2O_5	19.5	26.5	35.1	39.4
K_2O	8.9	3.3	20.8	74.5

Results

Table 19 summarizes the nutrient balances for cultivated plots. The balances for N and K were significantly higher in the hamlets than in the village. The highest balances were among the Fulani. This system fared well because the cultivated plots were smaller and large cattle herds were able to supply them with abundant manure. Households in the hamlets used larger doses of mineral fertilizer than villagers did, and living directly adjacent to their fields allowed them to nurture their crops better and obtain higher yields. Therefore, the hamlet residents could devote a greater proportion of their cotton income to fertilizers.

Discussion

The nutrient balance was again based on Stoorvogel and Smaling (1990) and it included all five inflows and all five outflows. The innovative aspect of the study was the participatory approach, where the focus was on the perceptions of farmer groups and not on the INs and OUTs per se. Furthermore, the farmers determined their own nutrient stocks and flows diagram.

Nutrient balances for niche management

Soil fertility management in southern Ethiopia

The broad objective of the study was to examine soil nutrient balances at small spatial scales. Earlier survey reports had indicated declining crop yields, and the farmers attributed this to declining soil fertility. The study set out to explore whether there was any evidence of negative balances of major plant nutrients (N and P) in the area, and whether the balance was related to the AEZ and the socio-economic status of the farmer (Elias, Morse and Belshaw, 1998).

Four case-study farms were selected in each of two AEZs (highland and lowland), representing four socio-economic groups of farmers in terms of their resources: rich, medium, poor and very poor. Differentiation of households into socio-economic groups was carried out by the farmers utilizing a wealth-ranking exercise based on local criteria centred primarily on draught oxen ownership and livestock herd size. Draught oxen ownership is the major local indicator of wealth and is a central criterion in any attempt to classify households. The differentiation of households into socio-economic groups was:

- Rich: farmers owning more than two oxen and a sizeable number of other livestock.
- Medium: farmers owning two oxen and about half the number of livestock as the rich group.
- Poor: farmers owning or sharing one ox and also not owning any breeding cows.

- Very poor: farmers not owning any cattle, but occasionally owning one or two goats or sheep (they borrowed animals for draught power and manure production).

Methodology

In order to assess declining soil fertility, this study used the nutrient balance rather than the technically more difficult approach of comparing changes in soil nutrient stocks (Pieri, 1983). With the nutrient-balance approach, the quantities of nutrients entering and leaving a field are estimated, and the balance (input - output) calculated. Balances were calculated for all fields within the farms, and the farm balances were calculated by aggregating input and output data for all fields. This study examined only N and P as they are the two nutrients identified as particularly deficient in Kindo Koisha soils. The N and P balances were calculated from a combination of four input and five output processes. The input flows were:

- mineral fertilizer (IN1);
- organic matter (IN2), comprising manure and household refuse (IN2a), and leaf litter (IN2b);
- atmospheric deposition (IN3);
- BNF (IN4).

Sedimentation, identified as IN5 in the original model, is not relevant as there are no irrigation schemes or flood plains in Kindo Koisha.

The output flows were:

- removal in harvested products (OUT1);
- removal in crop residue (OUT2);
- leaching (OUT3);
- denitrification (OUT4);
- water erosion (OUT5).

The eight farmers included in the case studies used diagrams to identify the perceived key nutrient input and output flows on their farms. These flows were measured over one production year in order to produce a nutrient balance sheet for each field. Quantification of N and P in the input and output flows was achieved through a combination of different methods: field measurement, use of empirical quantitative relations (i.e. transfer functions), and assumptions based on secondary data from a variety of sources. Tables 20 and 21 summarize the type of data required and the method of quantification for each of the input and output functions.

For both N and P, primary data were obtained as applicable on type and quantity applied of fertilizer, manure, households refuse and leaf litter. The number of baskets of manure transported and the site of application were monitored on a daily basis, and the fresh weight of manure per basket was measured. Composite samples of fresh manure from the livestock pen were collected and analysed for moisture content and composition of N and P at the International Livestock Research Institute (ILRI). The manure samples were oven dried at 105 °C before analysis, and moisture contents of 60 percent (highland) and 50 percent (lowland) were used to convert manure input into nutrient input.

Local data on atmospheric deposition (IN3) were not available in the area, hence atmospheric deposition of N and P were calculated as the square root of the average annual rainfall using the regression equation derived by Stoorvogel and Smaling (1990). The regression coefficients

TABLE 20
Type of data required and quantification method for the four input processes employed in calculating N and P balances

Input process	Code and nutrients	Data required	Method of quantification
Mineral fertilizer	IN1 (N & P)	Type of fertilizer applied	Field measurement
		Amount of fertilizer applied	Field measurement
Manure	IN2a (N & P)	Amount of manure applied	Field measurement
		Nutrient content of manure	Laboratory analysis
Leaf litter	IN2b (N & P)	Amount of leaf litter collected	Farmer estimation
		Types of trees used for leaf collection	Field observation
		Nutrient content of litter	Laboratory analysis
Deposition	IN3 (N & P)	Average annual rainfall	Rainfall records
		N and P deposition in rainfall	Transfer functions
BNF	IN4 (N only)	Type of legume grown	Field observation
		Grain and residue yield of legume	Field measurement
		Nutrient content of grain and residue	Laboratory analysis
		Percentage of uptake attributed to symbiotic fixation	Secondary data

TABLE 21
Type of data required and quantification method for the five output processes employed in calculating N and P balances

Output process	Code and nutrients	Data required	Method of quantification
Harvested product	OUT1	Crop yield	Field measurement
	(N & P)	Nutrient content of product	Combination of laboratory analysis and estimations
Crop residue	OUT2	Residue yield	Field measurement
	(N & P)	Destination of residue	Field observation
		Nutrient content of residue	Combination of laboratory analysis and estimations
Leaching & denitrification	OUT3 & OUT4	Average annual rainfall	Rainfall records
	(N only)	N in applied fertilizer	Field measurement
		N in applied manure	Field measurement records
		Leaching & denitrification of soil N & applied N	Estimate (transfer function)
Erosion	OUT5	Average annual rainfall	Rainfall records
	(N & P)	Erodibility (K)	Secondary data
		Slope length (L)	Estimate based on field measurement
		Slope gradient (S)	Secondary data
		Land cover (C)	Secondary data
		Management factor (P)	Secondary data
		Nutrient content of sediments	Secondary data

were 0.14 for N and 0.023 for P. Haricot bean provided the only N input from biological fixation (IN4). Grain and residue yields of haricot bean were measured in the field, and the nutrient composition of these products was determined through chemical analysis at the ILRI. Like Smaling, Stoorvogel and Windmeijer (1993) working with this crop on Nitosols in Kenya, it was assumed that 50 percent of the bean N requirement was derived from biological fixation.

Removal of nutrients in crop products (OUT1) and residues (OUT2) were quantified through a combination of primary data and estimates based on secondary data. Subsamples of harvested products and residues of maize, enset, teff and haricot bean were analysed for N and P content at the ILRI laboratory. This was necessary because reported values for N and P composition of maize vary considerably in the literature, and secondary data were not available for N and P content of enset, teff and haricot bean. The N and P composition of sweet potato, taro and sorghum were estimated using FAO data. Removal of nutrients in crop residue was quantified by taking into account the fraction of residues removed from the field for feed and fuel. In the highlands, about 80 percent of crop residue was completely removed from the field, but in the lowland the proportion was 30–50 percent. The high and low ranges of nutrient composition of maize were determined using the mean values of the lowest and highest quartiles of 15 data points from several countries in SSA.

No quantitative information was available on leaching and denitrification within the study area or in comparable AEZs nearby. Therefore, N loss through leaching (OUT3) and denitrification (OUT4) were estimated using the transfer function of Smaling, Stoorvogel and Windmeijer (1993). These authors derived multiple regression equations for OUT3 and OUT4 using the generally accepted determinants of rainfall, soil texture (clay content), soil N and application of fertilizer (IN1) and organic matter (IN2). The multiple regression equations are of the form:

$$\text{OUT3} = 2.3 + (0.0021 + 0.0007 \times F) \times R + 0.3 \times (\text{IN1} + \text{IN2}) - 0.1 \times UN$$

where:

F = soil fertility class, highland soils assumed moderate (2) and lowland soils low (1);

R = rainfall (annual average, in millimetres);

UN = total N uptake (in kilograms per hectare);

$$\text{OUT4} = X + 2.5 \times F + 0.3 \times (\text{IN1} + \text{IN2}) - 0.1 \times UN$$

where X = ‘relative wetness’, an LWC specific fixed value estimated at 5 kg N/ha/year for uncertain rainfall areas of Africa such as Kindo Koisha.

Volatilization of ammonia and burning can also cause gaseous nitrogen losses. However, volatilization is generally recognized as negligible in crop fields of highly-weathered acidic soils of east Africa. Therefore, it was not included in this study. In the study area, crop residue is used intensively as feed and not burnt in the field. Therefore, nutrient losses through burning were assumed to be negligible.

Soil erosion only occurs in the highlands of Kindo Koisha as the lowlands are mostly flat. Soil loss from erosion was estimated using the simplified and adapted version of the USLE (Hurni, 1985). The equation predicts soil loss as a function of rainfall erosivity, soil erodibility, slope length, slope gradient, land cover and land management (as explained above).

Nutrient loss in the eroded sediment was calculated using the total N and P composition of eroded sediments determined by Belay (1992) for the study area: 0.22 percent total N and 0.07 percent total P.

Values for N and P balances estimated using the procedures described above are regarded as the most probable because they have been calculated using the most likely assumptions for Kindo Koisha. However, some of the parameters and processes, such as atmospheric deposition (IN3), leaching (OUT3), denitrification (OUT4) and erosion (OUT5), were estimated from secondary data, within which there is some variability. In order to incorporate some of this uncertainty, ‘optimistic’ and ‘pessimistic’ values (based on assumptions considered to be extreme for the area) were also calculated. The result was an uncertainty range likely to encompass the 'real' value. The procedure for quantifying optimistic and pessimistic values follows the one used by Van der Pol (1992). The optimistic balance is calculated by combining high estimates of nutrient inflows and low estimates of nutrient exports. Conversely, the pessimistic values combine high values for export with low values for input.

Because of the lack of data for other crops, the high and low estimates of N and P export in harvested products and residues of maize were used to estimate ranges for OUT1 and OUT2. The optimistic and pessimistic values of atmospheric deposition and leaching were derived using high and low ranges of rainfall in the regression equation. The high and low values for the rainfall erosivity factor (*R*) adapted for the area was used to calculate the optimistic and pessimistic ranges of erosion (OUT5). The optimistic value was calculated by using the lower range of the rainfall, which corresponds with an *R* factor of 441, and the pessimistic value was calculated using the high rainfall range, which gave an *R* factor of 890.

Results

The N balances were negative for all household groups, while the P balance was positive for most farms (Table 22). Poorer farmers had lower N depletion rates, which may seem contradictory. However, they can compensate for lower mineral fertilizer inputs by intensive soil enriching and nutrient conserving practices, including: rational use of available manure; systematic management and recycling of crop residues; collection of leaf litter; and improved soil conservation. The differences between the farm components were very large. The enset, taro and darkoa (homestead) fields received many inputs and therefore had a positive or neutral balance, but the shoka (out fields) had very negative balances owing to low inputs.

TABLE 22
Farm nutrient balances for different household groups

	Households	N	P
		(kg/ha)	
Highland	Rich	-47	11.7
	Medium	-51	4.8
	Poor	-19	3.6
	Very poor	-6	1.1
Lowland	Rich	-49	30.5
	Medium	-41	17.3
	Poor	-55	3.8
	Very poor	-20	-1.6

Discussion

The methodology for the nutrient-balance calculation was based on Stoorvogel and Smaling (1990), and all five inflows and all five outflows were calculated. The additional value of this study is the calculation per household group and per farm component (enset garden, taro root, darkoa and shoka fields). This shows the diversity and complexity of the farming system in the Kindo Koisha area of Ethiopia and the impact of the different management of each social class.

Banana-based land use system in the northwest of the United Republic of Tanzania

Farmers in Bukoba District, in the northwest of the United Republic of Tanzania, are facing a continuous decline in crop productivity. Nutrient flows in land use systems are not well documented. The study, supported with data collection, presents the nutrient balances for various AEZs. The objectives of the study were: (i) quantify nutrient flows of the home garden; (ii) assess the sustainability of the banana-based land use system in different AEZs; and (iii) identify possibilities and set strategies for increasing nutrient use efficiency (Baijukya and Steenhuijsen de Piters, 1998).

The Bukoban agro-ecosystem is characterized by a combination of: a banana-based home garden (kibunja); small fields with annual crops (kikamba), usually of no permanent character; and grasslands (rweya). The study considered nutrient balances of the banana-based land use systems in the kibanja because this LUS produces the vast majority of agricultural produce of the farm households.

Methodology

The authors of the study adopted the nutrient-balance calculation model of earlier literature-based studies (e.g. Janssen, 1993) and verified or modified their data. Nutrient flows were quantified according to the nutrient-balance model proposed by Stoorvogel and Smaling (1990).

Data on nutrient inputs (IN1 and IN2) and outputs (OUT1 and OUT2) through harvested crops (bought, consumed and sold), and the use of grass and ash produced in the households, were collected in three villages in three AEZs. These villages represented variations found in the district. Data on farm size, bean and coffee production were available from earlier work in these areas.

Fifteen farmers per village were selected for data collection; six were monitored closely and the others were visited regularly as ‘check farmers’. Cattle and non-cattle owners were considered as distinct categories of farmers, which were included in the study. The closely monitored farmers were provided with scales (to weigh the bananas and root crops they harvested and grasses they used) and ledgers (to keep records of crops and grasses they used). The ‘check farmers’ were interviewed on grass use and banana production, and samples of banana bunches and grass bundles were weighed for verification. The closely monitored farmers were visited at two-week intervals from August 1993 until October 1994.

Different samples of banana (pulp, peal and stalk), root and tuber crops, and grasses (categorized into mulch, carpet and brewing) were collected from the respective villages. The collected samples were dried to determine their dry matter, and a part of the dried samples were analysed on total N, P, K, Ca, Mg and sulphur (S). Data on nutrient input through application of farmyard manure were available from other studies conducted in the area. Local data on wet deposition were not available. Data on average nutrient contents of four rainwater samples were collected at the research station in order to predict wet deposition. Nutrient input was linked to the concentration of the individual element in rainwater and the mean annual rainfall received in different zones. Inputs through dry deposition were assumed to be negligible given the humid environment.

Common bean (*Phaseolus vulgaris*) is the only leguminous species grown in the kibanja. N contribution by beans through biological N_2-fixation (IN4) was estimated as 50 percent of total plant uptake in aboveground biomass. The contribution to the N balance through asymbiotic N fixation was estimated using annual rainfall data of each zone. Input of nutrients through sedimentation (IN5) was not considered important in the perennial home gardens.

Data on nutrient losses of home gardens through leaching (OUT3) were available for the Bukoban high rainfall zone (Van der Eijk, 1995). Nutrient losses were calculated on the basis of nutrient concentrations in the percolating water. The rainfall, rain days, rain months and potential evapotranspiration (PET) data were used to calculate the percolation water in different AEZs.

The PET for Bukoba was reported to average 3.5 mm/day, and the rain days 260, 220 and 180 for the respective zones. For the Bukoban high rainfall zone, the percolating water was found to be 990 mm/year and the leaching index was assumed to be 1. For the Karagwe-Ankolean low rainfall zone (annual rainfall of 900 mm/year), the percolating water was found to be 270 mm/year and the leaching index 0.27. Applying the same procedure, the leaching index for the Bukoban medium rainfall zone was estimated at 0.64. Nutrient losses via leaching for the Bukoban high rainfall zone were extrapolated to the other zones using the calculated leaching indices. S losses were estimated on the basis of Ca:Mg:S ratios of Van der Eijk (1995) and Umoti, Atage and Isnemila (1983).

Denitrification was considered to be the most important process through which gases are lost (OUT4). Gaseous losses through volatilization were not considered important as alkaline soils are rare found in Bukoba. The percentage of mineralized soil N was calculated first by determining the fraction of soil organic matter that decomposes annually (k) and the humification coefficient of fresh organic matter (h). It has been reported (Janssen, 1984; Janssen, 1993) that k is dependent on temperature and h on the nature of fresh organic matter. The mean annual temperature in Bukoba is 21 °C and the k value was assumed to be 5 percent. The dominant fresh organic matter forms applied in the home garden are banana residues, grass and farmyard manure. Their h values were assumed to be 0.2, 0.3 and 0.5, respectively. The relationship between soil organic matter (SOM), effective organic matter (OM), fresh organic matter (FOM), k and h was reported to be:

$$OM = k \times SOM = h \times FOM$$

Using the above information, and by assuming a soil bulk density of 1.25 g/cm^3 and a carbon to nitrogen ratio of 11, the mineralization for home garden soils in different zones was calculated.

The denitrified soil N (DN soil; percentage of mineralized N) was calculated using a transfer function:

$$DN = -9.4 + 0.13 \times \text{clay content} + 0.01 \times \text{annual rainfall}$$

For soil with N mineralization of 330 kg/ha/year, 25 percent clay and 1 900 mm of rain, the DN is 13 percent. Thus, the N loss is 42 kg/ha/year.

Nutrient output through erosion (OUT5) was not considered important because of the absence of traces of erosion in farmers' fields.

The major nutrient fluxes in home gardens in the different AEZs were translated into a general input-output model (Table 23). The nutrients considered in the nutrient-balance calculations were N, P, K, Ca, Mg and S. Except for P, which is available in abundance, these nutrients were reported limiting in most Bukoban soils. The determinants used to calculate the balances were mostly scale-neutral. Therefore, they can be used to calculate the balances at plot, farm and village levels.

Results

Table 24 shows that nutrient balances were negative for home gardens without cattle and positive for those with cattle. These results suggest that intensification of cattle is a solution for declining soil fertility. However, the results are misleading to a certain extent. The home garden is only one component of the farming system, and grasslands have to produce the vast amount of cattle feed required, which causes exhaustion of the soil.

Table 23
Nutrient flows at farm level

Flows			Nutrients
Input	IN1		Mineral fertilizers
	IN2		Organic inputs
		IN2a	Grass (mulch, carpet and brew)
		IN2b	Concentrates for dairy cattle
		IN2c	Fodder grasses fed to dairy cattle
		IN2d	Manure from indigenous cattle grazing outside the farm
	IN3		Atmospheric deposition in rain
	IN4		BNF by beans and free-living bacteria
	IN5		Sedimentation[a]
	IN6		Subsoil exploitation by coffee and other perennial trees[b]
Output	OUT1		Harvested crops, banana, coffee, beans, roots and tubers
	OUT2		Crop residues and manure leaving the farm[a]
	OUT3		Leaching below the rootzone
	OUT4		Gaseous losses
	OUT5		Runoff and erosion[a]
	OUT6		Human faeces in pit latrines[b]

[a] Not relevant in kibanja system.
[b] Not considered in the present study.

Table 24
Nutrient balances of banana farms

Zone	Farm nutrient management level *	N	P	K
		(kg/ha/year)		
Bukoban high rainfall	1	-76.2	-4.9	-50.0
	2	-73.9	4.2	-41.2
	3	-7.5	10.8	-6.4
	4	7.0	12.3	15.5
	5	80.5	42.8	198.7
Bukoban medium rainfall	1	-49.0	-1.7	-39.8
	2	-45.0	-1.0	-22.8
	3	-6.7	8.0	-4.8
	4	1.7	8.8	4.3
	5	30.8	23.5	90.9
K-A low rainfall	1	-27.9	-2.7	-30.1
	2	-25.1	-2.0	-20.6
	3	-8.7	1.6	-15.1
	4	-3.9	2.4	-8.8
	5	11.0	8.9	32.1

* Banana farm management level: 1 = farm with no cattle and without brewing; 2 = farm without cattle but brewing; 3 = farm with indigenous cattle but use no bedding; 4 = farm with indigenous cattle and use bedding; 5 = farm with improved (zero-grazing) cattle.

Discussion

This study is an example of niche management, in this case the banana-based farming system in the United Republic of Tanzania. The methodology was based on Stoorvogel and Smaling (1990) and not adapted significantly. Again, a differentiation between farmers was made, in this case between the intensity of cattle keeping in combination with the banana-based system.

Land use types in eastern and central Uganda

The aim of the study was to estimate the nutrient balances at the crop, LUT and farm levels, and to estimate the impact of adopting alternative practices on nutrient balances and productivity. Nutrient balances were estimated for small-scale farming systems at four subhumid, medium-altitude locations in eastern and central Uganda. Nutrient flows were estimated using data from several sources, including farmer interviews, observations of the farming systems, soil analyses, and the output of simulation models (Wortmann and Kaizzi, 1998).

A survey was carried out in four districts of central and eastern Uganda during the second season of 1995 in order to gather the data needed to estimate nutrient balances at the field and farm levels. The characteristics of the locations differ but there are similarities: two major cropping seasons with mean annual precipitation of 1 050–1 300 mm, similar mean temperature, and similar crops (although their relative importance varies). Land use was divided into seven categories: banana-based systems, annual cropping systems, fallow, pasture, tree lots, napier grass plantings, and home gardens.

Methodology

Nine or ten farmers were interviewed at each location; where feasible, the validity of their responses was verified through observations. Their farms were mapped in order to show the size and use of various parcels of land. Detailed observations made on three parcels per farm included: slope, slope length, soil physical and chemical properties (texture, organic carbon, pH with 1:1 water, Olsen P, CEC, and total amount of N, P and K) at 0–20 cm and texture at 20–40 cm depth. Farmers were interviewed in detail concerning the use of the parcels of land and nutrient flows to and from the parcels. Observations were made and questions asked about other aspects of nutrient flows on a whole-farm basis including management and utilization of household wastes and farmyard manure, and sale and purchase of different commodities.

Farmers were asked to give mean yield estimates for the crops growing on parcels studied in detail. Their estimates covered an unrealistically wide range and were considered to be generally unreliable. Therefore, mean yield estimates were made based on government statistics and researchers' experiences with the crops in these areas. Nutrient contents for some commodities were determined through the analysis of materials collected in central Uganda. For other commodities, values reported elsewhere were used.

Soil erosion losses were estimated using the USLE. Nutrient enrichment of the runoff was assumed to be 1.5. No attempt was made to estimate sedimentation although it may be significant in the fallow and pasture LUTs. Leaching, volatilization and denitrification losses were estimated using the CERES Maize model (Ritchie *et al.*, 1989) with three soil profile descriptions, four seasons of typical rainfall, and sowing on 1 March and 15 August. The CERES Maize model is able to capture nuances in daily weather data and estimate their effects on N flows as a function of characteristics of a one-dimensional, multilayered soil profile and crop management conditions. Rainfall during the five-month periods of simulation ranged from 374 to 591 mm. The estimates of N losses were used in N balance calculations for all crops. The Quantitative Evaluation of the Fertility of Tropical Soils (QUEFTS) model (Janssen *et al.*, 1990) was used in the interpretation of soil test data. The QUEFTS model estimates nutrient availability during a season and soil productivity in terms of maize yield using data for organic carbon, soil pH in water, Olsen P, exchangeable K, and the totals for N, P and K.

It was assumed that ash and dry household waste produced per family were 20 and 100 kg/year. For grazing livestock, 50 percent of the faeces and urine were estimated to be deposited in the grazing areas, where N loss to volatilization was 10 percent. Nutrient losses from the farmyard manure were estimated to be: 50 percent of N, and 20 percent of P and K for livestock kept in open pens; and 20 percent of N, P, and K for those confined in a covered structure. The burning of manure resulted in the loss of 80 percent of the N and 20 percent of the P and K; 25 percent of the remainder was lost due to erosion and leaching.

Annual human consumption rates of N, P and K were assumed to be 4.00, 0.36 and 6.00 kg per capita. Although some of these nutrients are recycled through plant growth, no attempt was made to estimate the amount. Nutrients consumed by people were considered lost to the system. Burning of bean and soybean crop residues is common in Palissa District after threshing the crop at home. The ash is commonly used in cooking. The burning of crop residues was estimated to result in the loss of 80 percent of the N and 20 percent of the P and K.

Results

Table 25
Nutrient balance for major crops

Crops	N	P	K
	(kg/ha/year)		
Banana	-13.2	1.2	-35.7
Maize	-104.2	-13.6	-82.4
Bean	-40.4	-8.8	-42.7
Sweet potato	-71.3	-13.2	-78.9
Soybean	-121.5	-16.4	-68.3
Fallow	33.2	-1.5	-13.7
Pasture	19.2	-3.3	-30.7
Home garden	3.0	-1.8	-18.9

The small-scale farms in eastern and central Uganda were biologically, agronomically and economically diverse. However, the nutrient balances were negative in all locations, showing that the current systems are not sustainable even with the low productivity. The nutrient balances in the banana-based LUT were near neutral (Table 25), because of transfer of organic material from other LUTs. The annual crops had high nutrient losses because of removal with harvested products and erosion.

Discussion

The nutrient balance was based on Stoorvogel and Smaling (1990), but some flows were calculated differently. Leaching and gaseous losses were estimated with the CERES Maize model, which uses local soil data. This probably results in a better estimation than by using transfer functions as it is based on the local circumstances. This study made a greater differentiation in the organic inputs; mulching or application of crop residues, farmyard manure, ash and household waste were treated separately.

A sisal plantation in the United Republic of Tanzania

Hartemink (2001) describes several case studies on soil fertility decline in the tropics. The study emphasizes the importance of hard data on soil property changes in relation to soil fertility decline. It compares the results of the nutrient balances with actually measured soil changes. The case study on sisal plantations is based on experimental work in the Tanga Region of the United Republic of Tanzania. Sisal is an introduced fibre crop and is grown mainly on large plantations (Hartemink and Van Kekem, 1994).

Methodology

Two different approaches were used to monitor soil chemical properties. In one approach, soil dynamics were monitored over time at the same site. This approach is called chronosequential sampling or Type I data. Type I data show changes in a soil chemical property under a particular type of land use over time. In the other approach, soils under adjacent different land use systems were sampled at the same time and compared. This approach is called biosequential sampling or Type II data. The underlying assumption is that the soils of the cultivated and uncultivated land are the same soil series, but that differences in soil properties can be attributed to the differences in land use.

Soil properties of permanently cropped fields were compared with historical data from the 1950s or 1960s from the same field (Type I data). Topsoil samples were taken in sisal fields and in similar soils immediately outside the plantation that had never been cropped (Type II data).

A nutrient balance was calculated for a sisal field that had been cropped permanently since 1957. Yield and soil data (Rhodic Haplustox) were available from 1966 to 1990. The balance included the following nutrient inputs: wet deposition, non-symbiotic N fixation, and nutrients added with the planting material. Mineral fertilizer or organic inputs were not applied on the sisal and were therefore not taken into account. The wet deposition (part of IN3) and non-symbiotic N fixation (part of IN4) were calculated according to Stoorvogel and Smaling (1990). The input with planting material is necessary for sisal as at the beginning of a cycle thousands of small sisal plants (about 2 kg each) are brought to the field. The only nutrient output that could be fairly well quantified was removal with the harvested products. Crop residues were not removed from the field. Erosion was negligible, because sisal is a perennial crop with a grass cover between the rows.

Results

The resulting nutrient balances were negative for all nutrients (Table 26), especially K and Ca. The negative balance was confirmed by the decline in nutrient in the topsoil (0–20 cm) for all nutrients. For most nutrients, the nutrient balance was more negative than the actual soil changes. Only for N were the soil changes much more negative. This might be explained by the omission of important outflows, i.e. leaching and gaseous losses. Inclusion of these flows

Table 26
Nutrient balance and soil nutrient content of a sisal field, 1966–1990

	N	P	K	Ca	Mg
Input with rainfall (kg/ha)	115	19	75	213	105
Input with BNF (kg/ha)	19	0	0	0	0
Input with planting material (kg/ha)	32	10	35	87	13
Output with yield (kg/ha)	491	100	1 067	1 400	605
Difference (kg/ha)	-326	-71	-957	-1 100	-487
Nutrient balance (kg/ha/year)	-13	-2.8	-38	-44	-19
Content in 1966 (kg/ha)	5 764	52	369	996	355
Content in 1990 (kg/ha)	3 144	8	82	271	97
Difference (kg/ha)	-2 620	-44	-287	-725	-258
Soil changes (kg/ha/year)	-104	-1.8	-11	-29	-10

Source: Hartemink, 2001.

should make the nutrient balance for N more negative, while these flows are not so important for the other nutrients.

Discussion

This study is one of the few that deal with plantation crops. Soil fertility improving measures may have more impact on plantation crops because of better investment opportunities. Another interesting aspect of this study is the comparison of measured soil changes with nutrient balances. The study concludes that hard data is necessary for validating nutrient balances and improving understanding of soil processes. It also emphasizes the importance of long-term field experiments. The nutrient balance was based on Stoorvogel and Smaling (1990), but several flows were not included because of data availability issues (leaching and gaseous losses) and irrelevance (mineral fertilizer, organic inputs, erosion and sedimentation).

Soil fertility management in southern Mali

This study by Kanté (2001) is described in “Scaling soil nutrient studies” (FAO, 2003) together with the VARINUTS project (SC-DLO *et al.*, 2000) as representative microlevel studies. Microlevel studies provide a picture of the variation within a mesolevel unit. Relevant management factors can be included, and monitoring can check whether changes in nutrient management have a bearing on nutrient balances and farm income. In this particular study, farmers were classified in three ‘soil fertility management’ classes, instead of the ‘average’ farmer. The study focused on two villages in the cotton zone of southern Mali (M’Peresso and Noyaradougou), with strong and moderate pressure on land respectively.

Methodology

The study followed a participatory approach according to the PLAR methodology (explained earlier). Farm households classified one another into three nutrient management groups (1 = good management, 3 = poor management). The partitioning largely reflected the number of household members, possession of animals and manure, and carts. The classification was evaluated annually with farmers being promoted or relegated to another class.

The nutrient balance was based on Stoorvogel and Smaling (1990), but used mainly ‘partial balances’ for comparisons between farmers and villages. The partial balance included IN1 (mineral fertilizer), IN2 (organic inputs), OUT1 (harvested products) and OUT2 (crop residues). These flows are the ones that are most management related and they are also called ‘easy to measure’ nutrient flows. These ‘easy to measure’ flows can be quantified from farm survey data and they can also be expressed in monetary or labour units. The ‘difficult to measure’ flows (IN3, IN4, IN5, OUT3, OUT4 and OUT5) are not normally measured but estimated with transfer functions. IN2 was subdivided into animal manure and compost, and OUT2 was subdivided into crop residue removal by animals, removal by households, and burning.

Results

At first glance, both villages have comparable farming systems. Cotton is the basic cash crop and cereals such as maize, sorghum and millet the major food crops. Livestock is very important. However, a closer look shows that the pressure on land is considerably higher in M’Peresso (higher population density, higher ratio of cultivated land to total land) and, as a consequence,

Table 27
Observed differences between two villages, Mali

	M'Peresso	Noyaradougou
Fallow/cultivated land ratio	0.6	1.4
Total N in soil (g/kg)	0.20	0.31
Total P in soil (mg/kg)	126	171
Availability organic manure (tonne)	26	11
Mineral fertilizer use on cotton (kg/ha)	102	155
Crop residues as animal feed (%)	35	15
Crop residues as compost (%)	16	43
Crop residue burning (%)	3	16
Partial N balance for cotton (kg/ha)	58	22
Partial N balance for maize (kg/ha)	-30	2

Table 28
Partial nutrient balances for two villages, Mali

	M'Peresso			Noyaradougou		
	N	P	K	N	P	K
	(kg/ha)					
IN1	15.3	4.0	4.3	41.9	8.3	10.4
IN2	16.8	3.3	22.7	10.8	2.0	14.6
OUT1	18.7	2.2	4.7	25.2	3.3	6.3
OUT2	14.1	1.2	36.7	16.7	1.1	21.1
Partial balance	-0.7	4.0	-14.4	10.7	6.0	-2.4

the management of crop residues is more intensive in M'Peresso (Table 27). Similarly, one might say Noyaradougou has a labour shortage, which does not allow the villagers to recycle all crop residues. Manure application is higher in M'Peresso, while farmers in Noyaradougou use more mineral fertilizers to compensate (Table 28). Therefore, the partial nutrient balance is more positive in Noyaradougou.

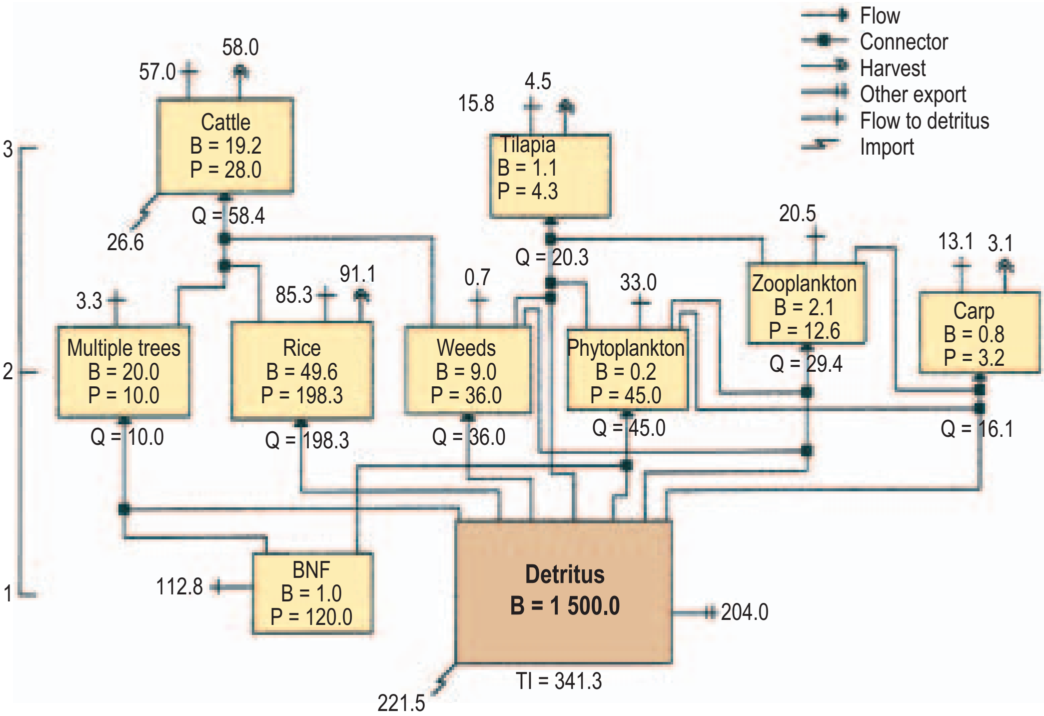
Discussion

The study is a good example of INM in the cotton zone of Mali. The participatory approach and the division into farmer classes make the results more useful, because the 'average' farmer does not exist. The partial balance is useful for comparing different nutrient management strategies. However, in order to know more about the sustainability of the system, one should use a complete nutrient balance. This is because the partial nutrient balance does not express indirect related nutrient losses, e.g. leaching and gaseous losses.

Integrated smallholder agriculture-aquaculture in Asia

A study by Dalsgaard and Prein (1999) applied a nutrient modelling approach to show how the combination of crops, trees, livestock and fish, that is integrated agriculture-aquaculture (IAA), helps in optimizing nutrient flows in Asian rice-based agro-ecosystems. Smallholder IAA is defined as diversification of agriculture in the sense that aquaculture (fish farming) is developed as a subsystem on a farm with existing crops, trees or livestock subsystems, or a combination thereof. A comparative on-farm study of integrated and non-integrated rice farming investigated N flows of four Philippine smallholder agro-ecosystems (Dalsgaard and Oficial, 1997).

Figure 17
ECOPATH flow diagram of a theoretical IAA farm system, kg N/ha/year



Note: B = average standing biomass, P = production, Q = consumption.
Source: Dalsgaard and Prein, 1999.

Methodology

Table 29
Published values of N flows into and out of fertilized rice agro-ecosystems

Inflows	
Dry and wet atmospheric deposition	1.5 kg/ha/year
Run-on with irrigation water	10 kg/ha/crop
BNF:	
Associative fixation in the rice rhizosphere	4 kg/ha/crop
Heterotrophic fixation associated with rice straw	2–4 kg/tonne straw
Heterotrophic fixation in flooded planted soil associated with organic debris	10–30 kg/ha/crop
Photodependent fixation by cyanobacteria	27 kg/ha/crop
Outflows	
Ammonia volatilization and denitrification	50–75% of fixed N
Erosion and runoff	Unknown
Leaching	Unknown

Source: after Dalsgaard and Prein, 1999.

The ECOPATH approach and software (Lightfoot *et al.*, 1993) were used for the modelling and analysis of the agro-ecosystems. This mass-balance framework provides a good basis for exploring the characteristics of nutrient flows and budgets in rice agro-ecosystems. ECOPATH diagrams individual farm components as boxes and indicates their biomass, production and consumption parameter values and linkages to other components, including detritus that denotes the soil resource base (Figure 17). The values for the different inflows and outflows were obtained from farm surveys and literature (Table 29).

TABLE 30
Agro-ecological performance indicators for four Philippine smallholder farm systems

	Fertilizer input and rice system			
	High; monoculture	High; diversified	Low; diversified & integrated	
	Farm (A)	Farm (B)	Farm (C)	Farm (D)
Surplus N (kg/ha/year)[a]	190	152	58	62
N balance (kg/ha/year)	-2	72	1	-9
N efficiency[b]	0.19	0.17	0.40	0.38
N yield (kg N/ha/year)	43	45	39	33
Gross margin (US$/ha/year)	250	750	625	600

[a] = lost from the farm system primarily in gaseous form and to a lesser extent through erosion/runoff.
[b] = ratio of system N harvest over all N inputs.
Source: Dalsgaard and Oficial, 1997.

Results

The on-farm investigation showed that economically attractive, productive and balanced systems can be generated and maintained through integrated natural resources management (Farms C and D – Table 30). It also showed that high application rates of mineral fertilizer are not necessarily associated with a positive nutrient balance (Farm A), but rather with high flows through the rice-based agro-ecosystem and high losses to the environment. High input diversification systems (Farm B) as yet have the highest gross margin.

Discussion

This case shows that nutrient balances can also be determined for other farming systems, such as the integrated agriculture-aquaculture system. N fixation is very important in these rice-based farming systems. However, outflows from leaching/deep percolation and erosion/runoff are almost unknown in such systems.

Chapter 3
General discussion

This chapter discusses important aspects in nutrient-balance studies that were not covered in Chapter 2. These issues are: uncertainties in nutrient balances; sampling for nutrient-balance studies; available nutrients versus nutrient flows; the use of spatial data; upscaling; and the impact of negative nutrient balances.

UNCERTAINTIES

The required accuracy and precision of a nutrient balance depend on the objectives and the originators of the study. The achievable accuracy and precision depend to a large extent on the complexity of the ecosystem and on the understanding of nutrient cycling and nutrient transformation processes. Biases and errors can introduce uncertainties. Bias is defined as systematic deviation and error as random variation. Five possible sources of bias exist: personal biases, sampling biases, measurement biases, data manipulation biases (including guesses), and fraud.

Sampling errors and measurement errors are sources of error. Sampling errors originate from spatial or temporal variations. Soils, crops and animal waste are notoriously variable in space and time and require well-designed sampling strategies. Measurement errors originate from variations introduced during the determinations of the sample volume and composition. The measurement error is usually much smaller than the sampling error. Table 31 presents an example of relative errors of nutrient flows for N and P budgets of farms in the Netherlands (Oenema and Heinen, 1999).

TABLE 31
Approximate values for the relative errors of N and P balances of farms, the Netherlands

Input	Error (%)	Output	Error (%)
Fertilizers	1-3	Milk	2-8
Manure	10-20	Meat	2-10
Plant material	5-20	Manure	10-20
Atmospheric deposition	10-30	Crops	5-10
Concentrates	5-10	Leaching	50-200
Forages	5-10	Runoff	50-200
		Volatilization	50-200
Total	5-15	Total	10-20

SAMPLING

To improve nutrient balances with validation and better input data, more field measurements are necessary. The fact that soil properties in particular are highly variable, highlights the need for good sampling strategies. A new technique for rapid estimation of soil properties, developed at the International Center for Research in Agroforestry (ICRAF), might prove useful in this respect. A scheme was developed for using soil spectral libraries for the rapid non-destructive estimation of soil properties based on diffuse reflectance spectroscopy. A diverse library of more than 1 000 archived topsoils from eastern and southern Africa was used to test the approach.

A portable spectrometer (0.35–2.5 µm) with an artificial light source scans air-dried soils. Integrated indicators of soil quality that relate directly to plant productivity and soil enrichment/ depletion processes (e.g. organic inputs and erosion) can be derived using visible-near-infrared reflectance spectroscopy.

The following soil properties can be determined: clay content, silt content, sand content, pH, organic carbon, exchangeable Ca, exchangeable Mg, exchangeable K, effective CEC, extractable P and N mineralization potential. Such indicators need to be readily measurable in order to permit monitoring of actual impacts of alternative farming practices on soil quality. This non-destructive technique allows large numbers of soil samples to be characterized rapidly (2 000 samples/week). Geo-referenced observations of the spectral quality index can also be interpolated spatially over large areas (> 1 000 km^2) using satellite imagery (Shepherd and Walsh, 2002).

In addition to a sound sampling scheme, correct sampling methodologies and measurements are important. High resolution data are required in order to assess accurately changes induced by INM strategies, which are often changes of 20 percent or less. These changes are detectable given the correct statistical design. However, systematic errors introduced in soil sampling methods and laboratory analysis generate data that are either always greater than or less than the actual sample mean. In soil sampling, one of the most widespread cause of systematic errors is sampling a soil to a given depth increment and assessing changes in that increment. Even minor changes in bulk density, which commonly occur during a trial as a result of natural processes or INM interventions, change the mass of a soil being sampled in a given depth increment. If the soil is compacted during a trial, this will result in an overestimation of nutrient stocks in a given depth increment, whereas if the soil is de-compacted, an underestimation will occur. Errors of 10–15 percent are not uncommon. Similar systematic errors can be introduced in the laboratory analysis. When combined with soil sampling errors, these generate misleading data and erroneous conclusions. Soil mass sampling eliminates sampling errors caused by depth sampling, but it requires methods not commonly employed (Wendt, 2003).

AVAILABLE NUTRIENTS

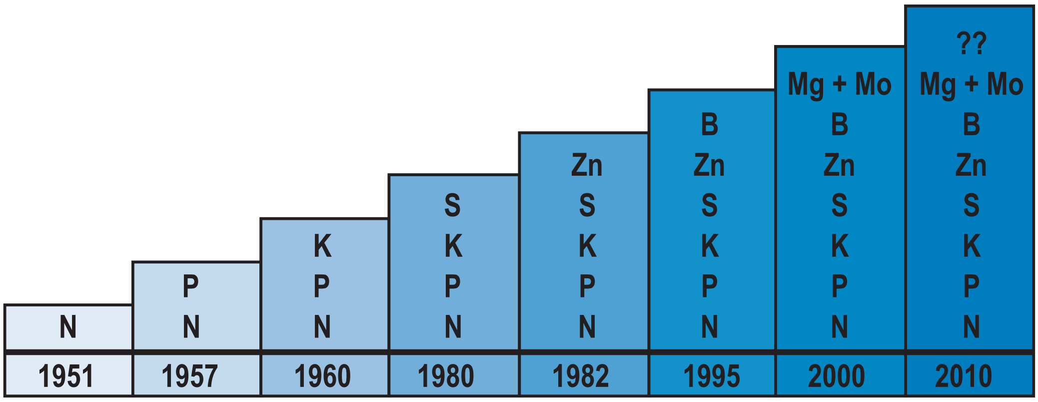
TABLE 32
Estimated fractions of available nutrients in each nutrient flow

	N	P	K
IN1	1.0	0.1	1.0
IN2	0.4	0.1	1.0
IN3	1.0	0.5	0.5
IN4	0.9	-	-
IN5	0.1	0.0	0.1
OUT1	1.0	1.0	1.0
OUT2	1.0	1.0	1.0
OUT3	1.0	1.0	1.0
OUT4	1.0	-	-
OUT5	0.1	0.0	0.1

Source: Janssen, 1999.

Available nutrients are conceived as the nutrients that are present in the soil solution at the beginning of the growing season or that will enter the soil solution during the season. In general, OUT1–OUT4 flows consist solely of available nutrients. OUT5 comprises flows of nutrients that are not immediately available, because they are preen in solid organic matter and inorganic particles (erosion) and flows of dissolved and, hence, available nutrients (runoff). The situation is more complex for inflows. The availability of IN1 and IN2 nutrients depends on the composition of the fertilizers and manure; it is affected by weather conditions, length of growing season and soil life. IN3 consists of direct available nutrients from precipitation and not direct available nutrients from dry deposition. For IN4 and

Figure 18
Time scale of nutrient deficiencies in Bangladesh



Source: Rijpma and Fokhrul Islam, 2003.

IN5, nutrients via symbiotic N fixation and irrigation are directly available, while nutrients via non-symbiotic N fixation and sedimentation are not. Table 32 shows estimates of available fractions of each nutrient flow.

Most nutrient-balance studies focus on the macronutrients N, P and K. However, plant growth depends on the most limiting nutrient, which might also be one of the micronutrients. Especially in countries with higher fertilizer use, the deficiency of nutrients changes from macronutrients to micronutrients because most mineral fertilizers consist of combinations of only N, P and K. This is illustrated in Figure 18 for Bangladesh, e.g. boron (B) deficiency in wheat, Mg deficiency in potato or maize and zinc deficiency in rice.

Spatial data

The understanding of spatial variation in crop response to environment and management is an essential component of agronomic research. The increasing availability of tools for spatial analysis, especially GISs, provides researchers with opportunities to improve analyses of spatial variation inherent to agronomic research. Benefits might include: improved selection of research sites or treatments; more quantitative assessments of the impact of climate and edaphic factors; and enhanced appreciation and improved presentation of how responses might vary over a target region. Typically, mesoscale variation would be of interest in field research conducted at one or more locations over a region where relevant map scales are of the order of 1:10 000 to 1:500 000. This might range from the county or district level to state or province level (White, Corbett and Dobermann, 2002).

Upscaling

Important for the upscaling of nutrient balances is first the determination of the system boundaries. Two methods for upscaling can be used: generalization and aggregation. With a generalization, a representative individual describes the characteristics of a group or population, e.g. fertilizer application data for one farmer is used to describe the fertilizer use of the whole village. Aggregation uses the information obtained for individuals to describe a population.

This involves grouping farms on the basis of one or more common properties. Frequency distributions can be used to describe the variability on a group scale. The temporal scale should also be taken into account. For this aspect, the size of the population is important because small systems (e.g. individual farms) change more rapidly and drastically than large systems (e.g. national livestock population).

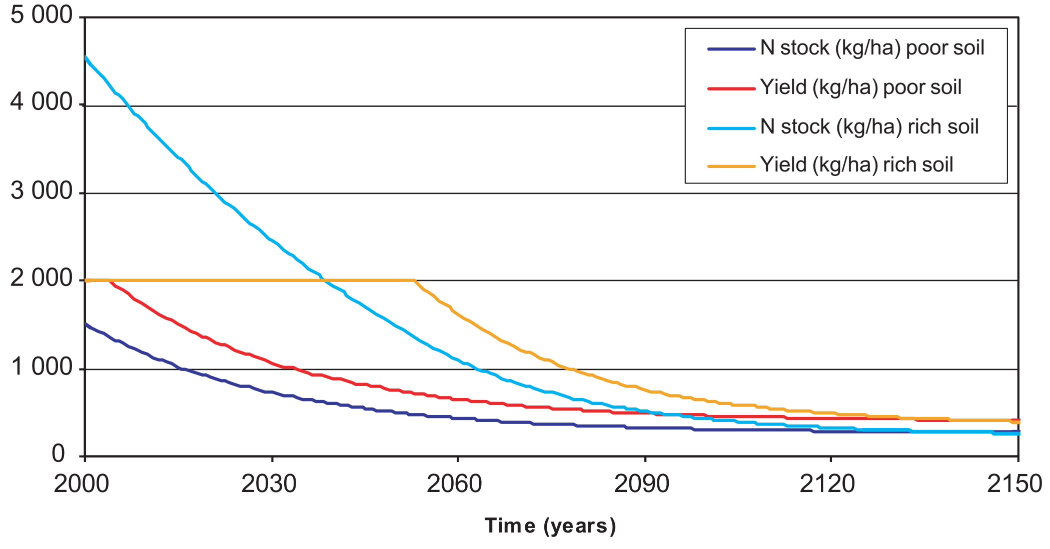
The paradox is that upscaling and loss of information are connected very closely. Information for the lower scale facilitates the constructing of nutrient balances for the higher scale. However, when the nutrient balance of the higher scale is determined, information is lost. Therefore, when presenting nutrient balances, the recommendation is to provide the information from the lower scales used for constructing the nutrient balance of the scale considered. Any scaling exercise is embedded in the data. Quantitative data with adequate spatial and temporal resolution on the use and management of fertilizers, animal excreta and environmental data are often very sparse (Van der Hoek and Bouwman, 1999).

IMPACT

The impact of a negative nutrient balance cannot be seen independently from actual soil fertility, i.e. the nutrient stocks. A negative nutrient balance on a rich soil will not affect yield in the short term, while on a poor soil, crop yield may decline each year as a result of nutrient depletion. At some stage in marginal areas, a negative nutrient balance may no longer affect production as yields reach a bottom-line level where natural inputs such as atmospheric deposition make up for losses.

Figure 19 shows an example of assessing the impact of nutrient depletion. Maize grown on a poor soil (N stocks of 1 500 kg/ha) without mineral or organic fertilizer inputs has a yield of 2 000 kg/ha. The yield will start to decline when the amount of available nutrients (mineralization rate of 3 percent) becomes lower than the necessary N uptake. This will happen after five years

FIGURE 19
Trends in yield and nutrient stocks for two soil types



Source: FAO, 2003.

on the poor soil, while nutrient depletion can continue without affecting yield for 55 years on the richer soil. In this scenario, the long-term equilibrium will be reached with very low yields (400 kg/ha) and N stocks (270 kg/ha). Hence, one could say that nutrient depletion often does not manifest itself clearly, but problems are likely to occur for the ‘future generations’ of the Brundtland definition (Brundtland, 1987).

Declines in yield and nutrient stocks can also be expressed in economic terms. Yield decline is a private (farmer) cost, whereas the decline in nutrient stocks is a social cost. Farmers will normally adapt their management when they experience yield decline. Where they do not have the means to increase fertilizer or manure use, they can adapt their management, e.g. make more efficient use of their fertilizer, use higher yielding varieties, make use of microvariability in their fields, and apply other INM techniques.

Chapter 4
Conclusions and caveats

Table 33 presents an overview of the nutrient balance of each of the cases reviewed in the preceding chapters. All the nutrient-balance methodologies used the sum of all inputs minus the sum of all outputs. Most approaches were derived from Stoorvogel and Smaling (1990), with five inflows and five outflows. Nutrient balances have become spatially explicit at the macrolevel, the focus is on farming systems at the mesolevel, and participatory approaches and niche management have been introduced at the microlevel.

Table 33
Overview of nutrient-balance studies

Scale	Site	Special	N	P	K	Source
			(kg/ha/year)			
Macro	Sub-Saharan Africa		-22	-2.5	-15	Stoorvogel and Smaling (1990)
	Africa*					Henao and Baanante (1999)
	China		-8	-4.5	-62	Sheldrick, Syers & Lingard (2003a)
	Ghana	Spatially explicit	-27	-4	-21	FAO (2003)
	Kenya	Spatially explicit	-38	0	-23	FAO (2003)
	Mali	Spatially explicit	-12	-3	-15	FAO (2003)
Meso	Kisii District, Kenya		-112	-3	-70	Smaling, Stoorvogel & Windmeijer (1993)
	Southern Mali	Optimistic & pessimistic view	-25	0	-20	Van der Pol (1992)
	Andhra Pradesh, India		18	-12	-38	Singh *et al.* (2001)
	Nkawie District, Ghana	Cocoa-based system	-18	-1.9	-20	FAO (2003)
	Wassa Amenfi District, Ghana	Cocoa-based system	-4	-0.5	-11	FAO (2003)
	Embu District, Kenya	Tea-coffee-dairy system	-96	-15	-33	FAO (2003)
	Koutiala Region, Mali	Cotton-based system	-12	1.4	-6.6	FAO (2003)
Micro	Southern Mali	Participatory approach	-8.2	8.5	7.4	Ramisch (1999)
	Southern Ethiopia	Different socio-economic households	-55 to -6	-1.6 to 30	-	Elias, Morse & Belshaw (1998)
	Northwest United Republic of Tanzania	Banana-based system	-76 to 80	-5 to 43	-50 to 199	Baijukya & Steenhuijsen de Piters (1998)
	Eastern and central Uganda		-125 to -3	-5 to -2	-11 to -9	Wortmann and Kaizzi (1998)
	United Republic of Tanzania	Sisal plantation	-13	-2.8	-38	Hartemink (2001)
	Southern Mali	Partial balances	-36 to -27	2.3 to 5.8	-32 to -11	Kanté (2001)
	Asia	Agriculture-aquaculture system	-9 to 72	-	-	Dalsgaard and Prein (1999)

*Nutrient balance ranged from -14 kg NPK/ha/year for South Africa to -136 kg NPK/ha/year for Rwanda

MACROLEVEL

At macrolevel, the nutrient-balance model raises awareness of soil fertility problems, indicates areas with nutrient depletion or accumulation, and gives a quantified picture of the nutrient flows. A macrolevel assessment can provide a basis for selecting areas for soil fertility improvement. A mesolevel study can then identify specific constraints, and it should reveal the best options.

MESOLEVEL

The introduction of mesolevel studies adds value to existing national- and farm-level approaches. Provided that sufficient data are available, mesolevel nutrient balances can be compiled properly. Mesolevel results provide information that cannot be deduced from macrolevel and or microlevel studies. The mesolevel offers a suitable entry point for policy-makers and private sector intervention, where macrolevel and microlevel are not appropriate for policy-making at the subnational level. Further methodological refinements are feasible through making them more spatially explicit (accounting for spatial variation in soils and climate) and through improving procedures for calculating nutrient flows and quantifying soil nutrient stocks.

MICROLEVEL

Many microlevel soil fertility studies have examined different regions and farming systems using different approaches and focuses, such as participatory approach, socio-economic household groups, economic aspects and INM techniques. With the NUTMON-toolbox, a standardized approach for nutrient monitoring has been developed. This enables comparisons between different studies. Microlevel studies provide a picture of the variation within a mesolevel unit. Relevant management factors can be included, and monitoring can check whether changes in nutrient management have a bearing on the nutrient balance and farm income. A participatory approach for the development and validation of locally specific packages should be promoted. It needs to combine examples of soil fertility management technologies with socio-economic and institutional measures that improve the adoption rate of the technologies.

CAVEATS

Validation

A major issue is the lack of sufficient validation and high uncertainties of the different nutrient flows. Large-scale and data-demanding studies are difficult to validate because of the large areas and the large amount of different data involved. This makes validation in the field difficult and expensive. It is not possible to validate all the nutrient flows at the macrolevel because this would require a massive number of samples. It might be possible to validate each nutrient flow at the microlevel, but these validations would then need to be scaled up to the mesolevel and the macrolevel. Other large-scale studies in the context of climate change and biodiversity research have similar validation problems. Some nutrient flows, such as leaching, can be validated by experiments. However, other flows, such as erosion or mineral fertilizer application, are more difficult to validate. As it is almost impossible to validate the whole nutrient balance, one can choose to validate only those specific flows that are deemed most important. For example, one can measure erosion in the field where this is one of the main losses according to the nutrient balance. These field observations and measurements should be performed according to a sound sampling scheme. Connecting validations of process research, e.g. studies of N_2O losses, to system research, such as this study, is both practical and feasible.

Gaps

Although the nutrient balance includes the most important nutrient flows, it fails to take some aspects into account. At the macrolevel, it does not incorporate large-scale processes such as forest burning and river-basin sediment transport. At the livestock level, it does include urine specifically although its nutrient content is quite different from that of dung. In addition, nutrient losses of urine are very high because of leaching and volatilization. Some other aspects, although not directly linked with the nutrient balance, can be of importance for the functioning of the whole agro-ecosystem. For example, below ground biodiversity has a direct effect on soil structure and the release of nutrients from organic material. Off-site effects, such as sedimentation into reservoirs and excessive nitrate leaching to groundwater, can also be related to the nutrient balance. Depending on the definition of the system, transnational imports and exports of products can be important flows in the nutrient balance, e.g. export of cash crops and import of fertilizers. Economic dynamics, such as the withdrawal of subsidies or trade liberalization effects, provide the all-important context that needs to be known before suggesting any improved nutrient management. Finally, it may be necessary to examine nutrients other than N, P and K, such as Ca and S, or organic carbon to link up with carbon sequestration research groups.

Usefulness for policy-makers

It is important that policy-makers be aware of any gaps in the nutrient balance, so they know what the limitations of the nutrient-balance model are. This raises the question of whether present outputs can serve as tools for policy-makers or whether further research is required. The nutrient-balance model proved to be a useful indicator for informed policy-makers, but the results as presented so far offer no entry points for intervention. The model raises awareness of soil fertility problems, indicates areas with nutrient depletion or accumulation, and gives a quantified picture of the nutrient flows at the macrolevel. At the mesolevel, it is possible to: (i) identify specific constraints; (ii) use quantified nutrient flows for planning purposes; and (iii) extrapolate results to other similar areas. Furthermore, outcomes might convince policy-makers to make action plans to improve soil fertility.

Presentation of outcomes

Model results expressed in terms of kilograms of nutrient per hectare are not very meaningful for policy-makers. They prefer outcomes expressed in terms of yield loss or in monetary values. The nutrient balance should have links to other tools and data in order to make it more useful. Combining a simple soil fertility/crop production model, such as QUEFTS (Janssen *et al.*, 1990), with the nutrient balance makes it possible to express nutrient depletion in terms of yield loss. Other attractive indicators to possibly attach to the nutrient flows and balance are the nutritive value of diets, food and cash needs, and equity indicators. Other options are to make use of decision-support systems and scenario studies. One way of making the nutrient-balance model more interactive is to link it to a model such as that of the conversion of land use and its effects (CLUE) (Veldkamp and Fresco, 1996), which simulates land use changes and its effects. It is also possible to combine the results with other GIS data, such as food security or poverty maps.

Specific problems for each scale level

In nutrient-balance calculations, each scale level has its own specific problems. At the macrolevel, the most important problems are: data quality; map interpretation; resolution differences; and groundtruthing. Intensive field checks in accordance with a sound sampling scheme can provide a partial solution. Soil properties and nutrient stocks might also be collected with new techniques for rapid estimation by reflectance spectroscopy (Shepherd and Walsh, 2002). At the mesolevel, the main problems are: lack of spatial data; incorporation of different management systems; and the absence of socio-economic explanatory factors, e.g. credit facilities and marketing. Spatial data will be increasingly available in the future. A classified satellite image and a DEM will improve the mesolevel nutrient balance significantly. At the microlevel, much research has already been done. The NUTMON-toolbox is a useful application, which also includes the monetary part. The issues at this level are: how to deal with diversity between and within farms; how to incorporate INM and integrated soil fertility management techniques; and how to scale up results. Possible options are: stratification in sampling methods; INM techniques in farmer field schools; and the use of GIS for upscaling.

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14

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