FAO
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BULLETIN

16

Plant nutrition for food security

A guide for integrated nutrient management

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by

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Preface

An expanding world population and the urgency of eradicating hunger and malnutrition call for determined policies and effective actions to ensure sustainable growth in agricultural productivity and production. Assured access to nutritionally adequate and safe food is essential for individual welfare and for national, social and economic development. Unless extraordinary efforts are made, an unacceptably large portion of the world's population, particularly in developing countries, could still be chronically undernourished in the coming years, with additional suffering caused by acute periodic shortages of food.

For biomass synthesis, which serves as the food resource for humans and animals, nutrient supply to plants is a prerequisite. Therefore, an adequate and appropriate supply of plant nutrients, is a vital component of a crop production system. Agricultural intensification, one of the basic strategies for enhanced food production, is dependent on increased flows of plant nutrients to the crops for securing high yields. Unless supported by adequate nutrient augmentation, the process of agricultural intensification would lead to land degradation and threaten the sustainability of agriculture.

In the past two decades, it has been increasingly recognized that plant nutrient needs in many countries can best be provided through an integrated use of diverse plant nutrient resources. An integrated plant nutrition system (IPNS) or integrated nutrient management (INM) enables the adaptation of the plant nutrition and soil fertility management in farming systems to site characteristics, taking advantage of the combined and harmonious use of organic, mineral and biofertilizer nutrient resources to serve the concurrent needs of food production and economic, environmental and social viability.

FAO has been engaged actively in the development of INM in the last two decades. Through its field projects, expert consultations and publications, the FAO has focused global attention on the need for large-scale adoption of INM. Propagation of the INM concept and methodology application at the farm level requires that the scientific community, extension workers, decision-makers, and other stakeholders concerned with agricultural development have a clear understanding of the subject.

This guide on integrated plant nutrient management, dealing with various aspects of plant nutrition, is an attempt to provide support to the ongoing efforts directed at enhanced and sustainable agricultural production. It seeks to bridge the scientific knowledge gap, and it presents updated information on plant nutrition with emphasis on INM. In helping stakeholders to improve their ability to identify and resolve constraints relating to plant nutrition – be they of a technical, economic, social or policy nature – and to demonstrate on the field practical ways of increasing production through efficient plant nutrition, the guide should assist in achieving the goal of food security.

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Thanks also go to J. Plummer for editing this publication and to L. Chalk for its preparation.

List of abbreviations and acronyms

^{40}K	Potassium-40
ADP	Adinosine diphosphate
AEC	Anion exchange capacity
AFS	Apparent free space
AISA	Adequate-input sustainable agriculture
Al	Aluminium
AN	Ammonium nitrate
ANP	Ammonium nitrate phosphate
APS	Ammonium phosphate sulphate
AS	Ammonium sulphate
As	Arsenic
ATP	Adinosine triphosphate
B	Boron
BCR	Benefit–cost ratio
BGA	Blue green algae
BNF	Biological nitrogen fixation
C	Carbon
Ca	Calcium
CAN	Calcium ammonium nitrate
Cd	Cadmium
CDU	Crotonylidene urea
CEC	Cation exchange capacity
CFS	Committee on World Food Security
Cl	Chlorine
CL	Critical level, critical limit
Co	Cobalt
CO_2	Carbon dioxide
CPM	Carbonation press mud
Cr	Chromium
CRH	Critical relative humidity
Cu	Copper
DAP	Di-ammonium phosphate
DRIS	Diagnosis and recommendation integrated system
DTPA	Diethylenetriamine pentaacetic acid
EAAI	Essential amino acid index
EDDHA	Ethylenediamine (o-hydroxyphenyl) acetic acid
EDTA	Ethylenediamine tetraacetic acid
ESP	Exchangeable sodium percentage

ET	Evapotranspiration
EU	European Union
F	Fluorine
Fe	Iron
FYM	Farmyard manure
GA	Gibberellic acid
GPS	Geographical Positioning System
H	Hydrogen
H_2S	Hydrogen sulphide
H_3BO_3	Boric acid
HCN	Hydrocyanic acid
Hg	Mercury
HYV	High-yielding variety
I	Iodine
IAA	Indole acetic acid
IBDU	Isobutylidene diurea
IFA	International Fertilizer Industry Association
IFOAM	International Federation of Organic Agriculture Movements
IKS	Indigenous potassium supply
INM	Integrated nutrient management
INS	Indigenous nitrogen supply
IPNS	Integrated plant nutrition system
IPS	Indigenous phosphorus supply
IR	Irrigation water requirement
Iw	Irrigation water
K	Potassium
KCl	Potassium chloride
LCC	Leaf colour chart
LIFDC	Low-income food-deficit country
LISA	Low-input sustainable agriculture
MAP	Mono-ammonium phosphate
Mg	Magnesium
Mn	Manganese
Mo	Molybdenum
MOP	Muriate of potash (potassium chloride)
MPP	Mono-potassium phosphate
N	Nitrogen
N_2	Dinitrogen
N_2O	Nitrogen dioxide
Na	Sodium
NENA	Near East and North Africa
NH_3	Ammonia
NH_4^+	Ammonium ion
Ni	Nickel

NO	Nitrous oxide
NUE	Nutrient-use efficiency
O_3	Ozone
P	Phosphorus
PAPR	Partially acidulated phosphate rock
Pb	Lead
PGPR	Plant-growth-promoting rhizobacteria
pH	Potential hydrogen (negative log of H^+ concentration)
PMD	Profit-maximizing dose
PR	Phosphate rock
PSB	Phosphate-solubilizing bacteria
PSM	Phosphate-solubilizing micro-organism
PSR	Pore space ratio
RNA	Ribonucleic acid
Rw	Rainfall
S	Sulphur
Se	Selenium
Si	Silicon
SO_2	Sulphur dioxide
SOM	Soil organic matter
SOP	Sulphate of potash, or potassium sulphate
SPFS	Special Programme for Food Security
SPM	Sulphitation press mud
Sr	Strontium
SSA	Sub-Saharan Africa
SSNM	Site-specific nutrient management
SSP	Single superphosphate
Sw	Water stored in soil profile
Th	Thorium
TSP	Triple superphosphate
U	Uranium
UAP	Urea ammonium phosphate
UN	United Nations
UNESCO	United Nations Educational and Scientific Cooperation Organization
USDA	United States Department of Agriculture
USG	Urea supergranule
V	Vanadium
VAM	Vesicular-arbuscular mycorrhizae
VCR	Value–cost ratio
WHC	Waterholding capacity
WHO	World Health Organization
WR	Water requirement
WUE	Water-use efficiency

Y	Economic crop yield
YMD	Yield-maximizing dose
Zn	Zinc

Chapter 1
Introduction

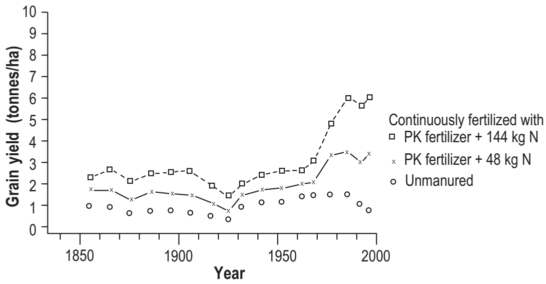
Of the essential material needs of humankind, the basic requirement is for an adequate supply of air, water and food. People have free access to the air they breathe. However, access to drinking-water and food, while easily obtained for some, is difficult for many. In addition to being physically available, these materials should also be of acceptable quality and continuously so.

Hunger and diseases have affected humankind since the dawn of history. Throughout time, there have been periods of famine leading to suffering and starvation, making the fight against hunger and the diseases caused by malnutrition a permanent challenge. For many centuries until about 1800, the average grain yield was about 800 kg/ha, providing food only for a few people. The main problems were the low fertility of most soils (mainly caused by the depletion of nutrients) and the great yield losses from crop diseases and pests.

Efforts to achieve freedom from hunger became successful only after the discovery of the nutritional needs of crops in the mid-nineteenth century. In order to supplement plant nutrients of low fertility soils or poor soils, the value of manures was stressed and mineral fertilizers were developed. Mineral fertilization started about 1880, became a common practice in the 1920s and adopted on larger scale since 1950. In Europe, cereal yields have increased at an annual rate of 1.5–2.5 percent for many decades, from an average of 2 tonnes/ha in 1900 to 7.5 tonnes/ha in 2000. The impact of fertilizers on wheat yields is best demonstrated by results from the Broadbalk Experiment, which was started in 1844 at the Rothamsted Experimental Station, the United Kingdom, and is still continuing (Figure 1).

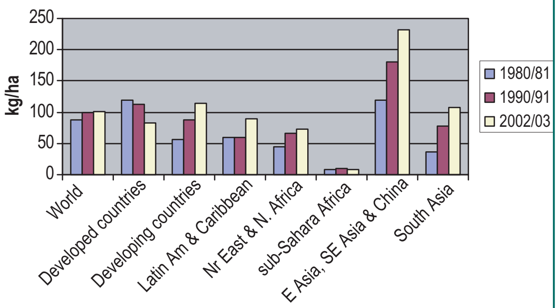
Even with restrictions on the present land area utilized for farming, a modern ecotechnological-oriented system of agriculture has the potential for large production increases. In comparison, a strictly environment-oriented agriculture without mineral fertilizers and other manufactured inputs, would be 2–3 times less productive, and incapable of sustaining even the present world population on

FIGURE 1
The effect of fertilizer on wheat grain yields in the Broadbalk Experiment, Rothamsted Experimental Station, the United Kingdom



Source: Johnston, 1997.

FIGURE 2
Mineral fertilizer consumption in terms of $N + P_2O_5 + K_2O$ on arable land, by region



Source: FAO, 2004a.

the already utilized land (IFPRI, 1995a).

PRESENT AND FUTURE DEMANDS FOR PLANT NUTRIENTS IN DEVELOPING REGIONS

As most of the additional food required must come from already cultivated land, intensification of agriculture with high (optimal but not excessive) and balanced use of nutrient inputs will be required. Even with a high degree of nutrient recycling through organics, mineral fertilizers will continue to be of central importance for meeting future food demands. Figure 2 shows the present level of mineral fertilizer application in developing regions. About 50 percent of all mineral fertilizer nutrients are used for the production of cereals (wheat, rice and maize), and 50 percent of all mineral fertilizer nutrients are consumed by China, the United States of America, and India.

Worldwide mineral fertilizer nutrient use is expected to increase from 142 million tonnes in 2002/03 to 165 million tonnes in 2009/2010, to 175 million tonnes in 2015 and to 199 million tonnes in 2030 (FAO, 2000a, 2005). The projections of mineral fertilizer demand differ considerably among the regions (Table 1). The largest share of mineral fertilizers will be used by East Asia, followed by South Asia. These two regions together will account for about half of world mineral fertilizer use by 2030. The growth rate in mineral fertilizer use is predicted to be highest in sub-Saharan Africa (SSA) and the Near East and North Africa (NENA).

Although the obstacles to higher food production seem almost insurmountable in problem areas, available land and inputs need not be limiting factors. However, production increases on low fertility soils will require special expertise, large investment in nutrients and major initiatives on a sustained basis.

TABLE 1
Mineral fertilizer use and projected nutrient demand to 2030 in developing regions

Region	$N + P_2O_5 + K_2O$	
	2002/03	2009/2010
	(million tonnes)	
Sub-Saharan Africa (including South Africa)	2.3	
Near East and North Africa	7.9	
East Asia	50.6	59.5
South Asia	20.9	25.7
Latin America	13.2	18.3
World	141.6	165.0

Source: FAO, 2000a, 2005.

Steps that promote optimal and efficient plant nutrition are required on a large scale in order to achieve food security. The aim should be to develop and adopt production systems that are productive, sustainable and least burdensome on the environment. Organic sources and recycling do not on their own suffice to meet increased demands for food on a fixed land area. On the other hand, because of possible environmental concerns and economic constraints, crop nutrient requirements often cannot be met solely through mineral fertilizers. Hence, a judicious combination of mineral fertilizers with organic and biological sources of nutrients is being promoted. Such integrated applications are not only complementary but also synergistic as organic inputs have beneficial effects beyond their nutrient content.

Therefore, the nutrient needs of such production systems can best be met through integrated nutrient management (INM). The concept of INM aims to increase the efficiency of use of all nutrient sources, be they soil resources, mineral fertilizers, organic manures, recyclable wastes or biofertilizers. Extension staff who are to translate research data into practical recommendations will need to take stock of both farmers' expertise and the applicability of research results. Available knowledge will need to be summarized competently and evaluated economically in order to provide practical guidelines for the adoption of INM by farmers having a range of investment capacities for achieving food security on a sustained basis. At the same time, plant nutrition research must continue to develop new techniques while refining existing ones based on feedback from the field.

Chapter 2
Food security and agricultural production

STRIVING FOR FOOD SECURITY

Past and present efforts

Nobody would have forecast 100 years ago that world agriculture could produce sufficient food, feed and other agricultural commodities for almost four times as many people as existed in 1900 (1 600 million in 1900 compared with 6 000 million in 2000). This apparently unattainable goal has been achieved through a combination of many factors, the combined impact of which triggered the so-called green revolution. Here, a combination of irrigation, fertilization and high-yielding varieties (HYVs) of crops resulted in the greatest progress ever made in food production. While it is difficult to envisage a repetition on this scale, further progress is certainly possible and urgently required.

National food self-sufficiency has been achieved in many countries through the combined efforts of farmers, industry, farm advisers and scientists. In the countries of Western Europe, in the United States of America and in other developed areas, there is a surplus of food production, and food is cheap. In the past, average workers with a family of four persons spent 50 percent of their income on food. This has now dropped to 15 percent, enabling them to purchase a wide range of other goods and services, the result being a higher standard of living.

Nonetheless, in large regions, consisting mainly of developing countries, hunger and malnutrition still exist. However, current food shortages are only partly caused by production problems. Disturbances to food production resulting from poor economic conditions, widespread poverty, civil war, inappropriate food pricing policies and logistical constraints contribute significantly to the problem. According to Borlaug (1993): “The dilemma is feeding a fertile population from infertile soils in a fragile world.”

Recent international efforts towards food security

In 1974, the World Food Conference proclaimed that every person has the inalienable right to be free from hunger and malnutrition. As this goal was not achieved after more than two decades (there being more than 800 million people, mainly in developing countries, without sufficient food), a new attempt was made at the World Food Summit in Rome in 1996 to renew the commitment at the highest political level to eliminate hunger and malnutrition, and to achieve sustainable food security for all people. According to the summit:

- Food security exists where all people, at all times, have physical and economical access to sufficient, safe and nutritious food to meet their dietary needs and food preferences for an active and healthy life.
- World food security is the concern of members of the international community because of its increasing interdependence with respect to political stability and peace, poverty eradication, prevention of, and reaction to, crisis and disasters, environmental degradation, trade, global threats to the sustainability of food security, growing world population, transborder population movements, and technology, research, investment, and financial cooperation.

The summit adopted the "*Rome Declaration on World Food Security*" and seven commitments as a "*Plan of Action*". The preliminary aim was to halve the number of undernourished people by no later than 2015. In addition, world food production should increase by more than 75 percent in the next 30 years to feed about 8 000 million people by 2025. To meet the target of halving malnutrition in developing countries by 2015, this number needs to be cut by at least 20 million/year, more than twice as fast as the current reduction of about 8 million/year. With a growing world population, this situation will worsen unless very determined and well-targeted actions are taken to improve food security.

It was against the above-mentioned background that the Special Programme for Food Security (SPFS), launched by FAO in 1994, was further strengthened, expanded and its implementation accelerated after the 1996 World Food Summit. The main objective of the SPFS is to help developing countries, in particular the low-income food-deficit countries (LIFDCs), to improve food security at household and national level through rapid increases in food production and productivity. It aims to achieve this by reducing year-to-year variability in food production on an economically and environmentally sustainable basis and by improving people's access to food. The programme is currently operational in about 75 countries. The FAO Committee on World Food Security (CFS) was made responsible for monitoring, evaluating and consulting on the international food security situation.

The underlying assumption is that viable and sustainable means of increasing food availability exist in most of the 83 LIFDCs but that they are not being realized because of a range of constraints that prevent farmers from responding to needs and opportunities. By working with farmers and other stakeholders to identify and resolve such constraints – be they of a technical, economic, social, institutional or policy nature – and to demonstrate in the field practical ways of increasing production, the SPFS should open the way for improved productivity and broader food access.

To achieve the target, the focus of action is at the country level. This means that food security is largely a national task. This is not easy for poor countries, and international organizations should give both advice and financial assistance.

For many well-fed people, food security refers less to food shortage and more to secure food (i.e. nutritious and safe food, free of toxic substances). According to the present-day demands of urban consumers, food should be abundant, diverse, tasty, nutritious, safe and cheap. Chapter 10 examines some of these aspects in detail.

Food production vs environment preservation

The discussion of potential food supply somewhat overshadows another aspect, namely the tolerance or capacity of the earth to support an ever-increasing number of people, including domestic animals. The production and consumption of essential goods such as food and industrial goods through intensive production systems is connected inevitably with some negative side-effects on the environment. Chapter 11 explores environmental issues in relation to plant nutrition.

Long before the maximum food production capacity of the world's agriculture is reached, retarding effects caused by environmental damage will become increasingly apparent. Global warming is one of its indicators. The damaging effects are caused partly by agriculture. Today, a common view is that agriculture places a heavy burden on the environment. However, this is so because people demand abundant and cheap food. The vital question is not only how many people this planet can feed and clothe but how many people it can support at an environmentally sustainable level.

FOOD SECURITY FOR A GROWING WORLD POPULATION

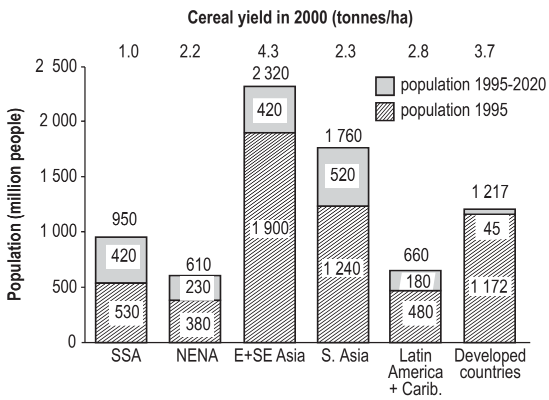
World and regional population until 2020

The world population doubled within 40 years after 1960. Despite some efforts to slow the growth rate, the global population will be about 7 500 million in 2020 according to a forecast by the United Nations (UN) using a medium-fertility model. In the more distant future, there may be 9 000 million people by 2050, and the number may stabilize at slightly more than 10 000 million after 2100 (IFPRI, 1997, 1999).

The population increase during the next two decades will occur almost entirely in 93 developing countries. With a growth rate of 1.5 percent/year, there will be 1 500 million more people by 2020, half of them urban and mostly young. This increase is comparable with the entire population of the developed countries (Figure 3).

The highest population growth (80 percent) will be in SSA, a region that already has

FIGURE 3
Population of developing regions and cereal yields



Note: SSA = sub-Saharan Africa, NENA = Near East + North Africa, E + SE Asia = East + Southeast Asia.
Source: IFPRI, 1999; Finck, 2001.

the most critical food supply situation. For NENA, the growth is predicted to be 40 percent, but the food supply is slightly better. East and Southeast Asia plus China have the smallest predicted population increase (20 percent), but the greatest existing population. The absolute increase is greatest in South Asia, with about 500 million people (40 percent). Latin America and the Caribbean are predicted to have strong population growth, but good food prospects as well.

In most regions, present food grain yields range from 2.2 to 2.8 tonnes/ha, but crop yields are only 1 tonne/ha in SSA. These yields are insufficient to feed the growing population. The task for the near future is to feed 700 million more people, and about 1 500 million more people in 2020. Thus, it is clear that:

- The increase in the global population will be entirely in the developing countries.
- An additional 1 500 million people will have to be fed by 2020, mainly in areas with present food shortages.
- SSA is the most critical region for future food supply.
- The bulk of the population (4 000 million) will have to be fed in Asia (East, Southeast and South Asia).
- Additional food must come mainly from higher production on existing agricultural land.

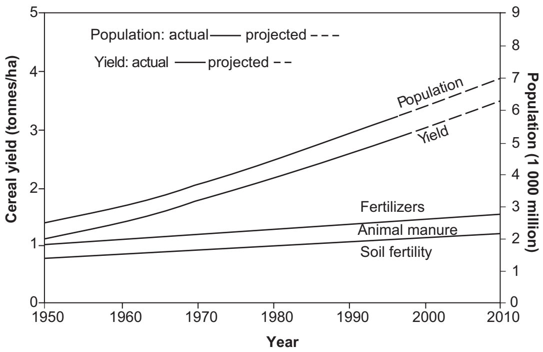
The necessity to feed so many more people in regions with "critical" food supply is an enormous challenge for food production and requires great efforts. One such effort will be to provide adequate crop nutrition so that the required amount of food and other crop products can be produced on a sustained basis.

Food production capacity of the world

An estimation of the biophysical limits of food production reveals that a much greater number of people than the expected equilibrium population (of about 10 000 million) could be supplied with sufficient food. According to FAO (2000a): "For the world as a whole there is enough or more than enough food production potential to meet the growth of effective demand." Intensive agriculture, while observing ecological requirements, can feed an ever-growing world population. Figure 4 highlights the impact that soil fertility, mineral fertilizers and animal manure have had on cereal production.

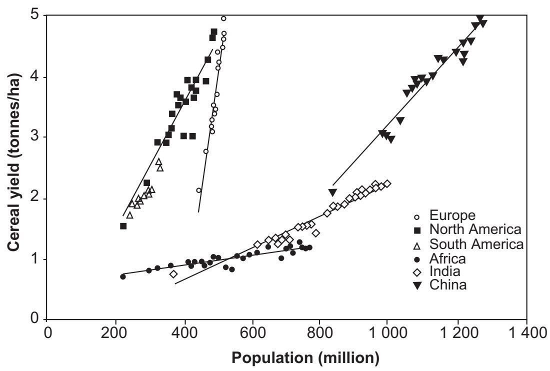
While enormous gains have been made in increasing cereal yields worldwide, there are very

FIGURE 4
Estimated global trends in population, cereal yields and source of plant nutrients



Note: The distance between the lines indicates the contribution from different sources.
Source: Kaarstad, 1997.

FIGURE 5
Relationship between human population and average cereal yields in six regions



Source: Evans, 2003.

large differences between the progress made in the different regions, particularly when compared with population growth in those regions. Figure 5 presents data for six key areas plotted by Evans (2003) using data from FAO production yearbooks. The population–yield relation is most favourable in North America and Europe while it is least favourable in Africa.

Food demand in developing countries

Compared with global food prospects, the challenge for the developing countries is much greater. Based on a projection from 1995 data, the global annual demand for cereals will increase by about 40 percent until 2020. Out of the globally required additional 700 million tonnes, developing countries will need about 600 million tonnes more cereals in 2020 (40 percent for China and India). About 80 percent of this additional food supply will have to come from already cultivated areas, as newly cropped land is likely to supply less than 20 percent of the increase.

The large increase in cereal demand will not only result from population growth but also from an increasing demand for meat, which will almost double to 30 kg/capita/year by 2020. As a consequence, the cereal demand for livestock feed will double, and the area of maize grown for animal feed is likely to exceed that of rice and wheat grown for human consumption. The cereal demand for 6 300 million people including both food and feed has been estimated at about 1 700 million tonnes, which amounts to 270 kg/capita/year or 0.75 kg supplying 2 800 kcal/day (IFPRI, 1999). Table 2 shows the regional food supply situation in 2000.

Developing countries have an average food and feed supply of about 250 kg/capita, which is considered satisfactory. In order to maintain this level in 2020, the average yield of 2.8 tonnes/ha in 2000 will need to increase to 3.5 tonnes/ha, but correspondingly less if the present cropping area is expanded. The above goal seems to be within reach, especially for Latin America and the Caribbean.

The situation in both NENA and South Asia is less satisfactory. With actual yields of about 2.2 tonnes/ha, both regions require a substantial yield increase in order to meet future demands (about 70 percent for NENA, and about 50 percent for South Asia). East and Southeast Asia consist of two rather different blocks. China has high yields and rather good food supply prospects, whereas the other countries of this region are in a position similar to South Asia. SSA is in the least

TABLE 2
Cereal production, supply and demand in developing regions

Data	Unit	Developing countries	SSA	NENA[1]	E + SE Asia	South Asia	Latin America + Caribbean
Population (2000)	million	4 800	590	400	1 860	1 320	510
Area, harvested	million ha	442	75	40	147	131	47
Production, total	million tonnes	1 227	75	88	633	305	133
Yield, average	tonnes/ha	2.8	1.0	2.2	4.3	2.3	2.8
Supply, total/capita	kg/year	256	127	220	340	230	260
Supply for human consumption/capita	kg/year	170	114	213	201	158	129
Demand 2020[2]:							
Additional; same level	million tonnes	384	45	46	156	101	39
Additional; yields required	tonnes/ha	3.7	1.6	3.4	5.4	3.1	3.6
Total; average demand[3]	million tonnes	1 575	238	153	x	440	165
Total; yields required[4]	tonnes/ha	3.5	3.1	3.8	x	3.4	3.5

Notes:
[1] Data for NENA estimated from FAO (1993a).
[2] Additional demand 2020 on basis of supply level of 2000.
[3] Total demand based on average supply of developing countries 2000 (250 kg/capita/year).
[4] Yields required: on cereal area in 2000.
x No average data because of great differences on the two blocks.

favourable position with a yield level of only 1 tonne/ha, which needs to rise by 50 percent just to maintain the supply level of 2000 in 2020. However, compared with Asia, there are greater prospects in Africa for using more fallow land.

Food quantity and quality, and malnutrition

About 800 million people in developing countries (20 percent of the population) are undernourished. The percentage of malnourished children is estimated to be 35 percent in SSA and 70 percent in South Asia. The term malnutrition refers mainly to suboptimal food energy intake, the required daily supply being 2 600–3 000 kcal (2 500 kcal/day corresponds to 0.7 kg of cereals per day or 250 kg/year). However, malnutrition in a complete sense also includes shortages of protein (essential amino acids), vitamins and essential mineral nutrients (e.g. phosphate and micronutrients).

Even with a satisfactory average supply, the problem of food shortage and malnutrition will persist in 2020, albeit at a reduced scale in most regions. However, in SSA, 15 percent of the people will probably still be undernourished in 2030 (FAO, 2000a). Sufficient food energy is only the first goal, and sufficient nutritious food the final one. In developing countries, protein deficiency (less than 50 g/day for an adult weighing 60 kg or shortages of some essential amino acids such as lysine) and a deficiency in vitamin A and iron (Fe) are common, particularly among women and children. A lack of Fe is associated with anaemia.

In order to prevent diseases resulting from nutritional deficiencies, the production of high-quality food is essential. Equally important is the knowledge of maintaining food quality through the selection and the preservation of its quality components during food processing and preparation. The neglect of food quality is widespread and by no means restricted to hungry people. Apparently well-fed people may also suffer from avoidable diseases induced by a deficiency in essential nutrients. Sufficient healthy food not only alleviates hunger but also prevents many diseases resulting from malnutrition. Chapter 10 examines the importance of adequate food of high quality and the role of plant nutrition in producing it.

FOOD PRODUCTION PROSPECTS IN DEVELOPING COUNTRIES

The food production prospects of developing regions with 6 700 million people in 2030 are of global concern. The challenge is to feed almost 2 000 million more people on the available land base. Data from a detailed study (FAO, 2000a) indicate that, for developing countries as a whole, food production will increase in the next 15 years by 2.1 percent/year, food demand by 2.2 percent/year and population growth by 1.4 percent/year. However, there are great regional differences. For example, in SSA, production may grow by 2.6 percent/year, demand by 2.8 percent/year, and population by 2.4 percent/year. The future food production in different regions will depend largely on land resources, inputs and the efforts to use them.

Land resources

Important indicators of available land resources are: total suitable land area for cropping, land suitability for different production systems, land actually put into production, cropping intensity, potential for expansion in area, and amount of irrigated land. Table 3 summarizes some basic data on these indicators for various developing regions.

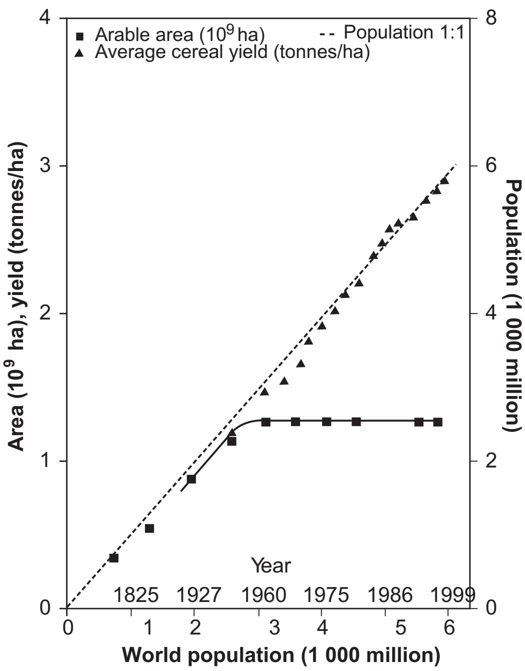
The comparison of total suitable land with actual arable land shows that there is large potential for increasing cropped area only in SSA and Latin America. NENA and South Asia have very little potential for area expansion. The estimated expansion in arable land by 2030 will be highest in SSA (25 percent) and lowest in South Asia (4 percent). Total harvested land is expected to show the highest increase (about 40 percent) in SSA and the lowest (14 percent) in South Asia in the next three decades. In terms of the proportion of harvested land that is

TABLE 3
Crop production base in developing regions

Developing region	Land suitable for cropping	Arable land used, 1997–2030	Harvested land 1997–2030	Very good + good land as % of suitable land	% of harvested land irrigated (1997)
	(million ha)			(%)	
SSA	1 031	231–288	146–205	75	3
NENA	99	87–94	71–86	26	37
East Asia	366	232–278	301–327	72	37
South Asia	220	207–216	230–262	88	43
Latin America	1 066	202–243	128–173	80	12
Total	2 780	960–1 079	877–1 053	76	29

Source: FAO, 2000a.

FIGURE 6
World population, arable area and cereal yields from 1800 to 1999



Source: Evans, 2003.

irrigated, there are large differences between the regions, the figure ranging from 3 percent in SSA to 12 percent in Latin America and about 40 percent in NENA and East and South Asia.

The suitability of land for cropping can be estimated from the percentage of very good and good land compared with total suitable land, the remainder being moderately suitable or unsuitable. The proportion of good land is very high in South Asia and Latin America (more than 80 percent), somewhat less in SSA and East Asia (about 73 percent), but only 26 percent in NENA.

Combining the prospects for land expansion and cropping intensification indicates that there is still considerable potential for higher food production in all regions. Figure 6 provides an indication of the considerable progress made in intensification. Whereas the arable area has remained constant since 1960, the average cereal yield per hectare has continued to increase linearly. In the future, SSA will face the greatest problems in this respect. In South Asia, India is a good example of the progress that has been made through intensive cropping.

There are already serious problems in large arid areas as a result of a shortage of irrigation water. This is caused by overutilization by agriculture and conflicts of interest between irrigation, drinking-water and industrial supplies. However, the problem of a shortage of freshwater may be reduced if an economical and environmentally acceptable method of desalinization can be developed.

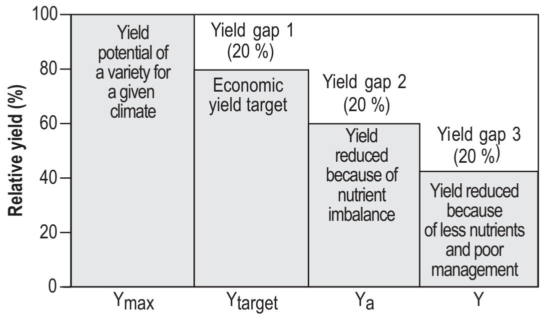
Plant nutrients

In time, the shortage of the essential plant nutrient phosphate may also seriously limit crop production. The major plant nutrients are nitrogen (N), phosphorus (P) and potassium (K). Of these, N is abundant in the air, and deposits of K are ample, but the phosphate reserves will become scarce. This may lead to conflicts for a share of phosphate fertilizers long before the phosphate rock (PR) deposits are exhausted. Only strict rules for recycling and efficient use could postpone this first serious shortage of an essential plant nutrient.

Yield levels

Worldwide, and also in many developing countries, the annual growth in cereal yields is still increasing although the global rate of increase has dropped from slightly over 2 percent to about 1.5 percent. For developing countries as a whole, the trend is from an increase of about 1.5 percent/year in the last few decades to less than 1 percent/year in the future (IFPRI, 1999). However, several countries in problem areas such as SSA (Ethiopia, Nigeria, etc.) show a stagnation in cereal yields (at a low level) or even a declining trend, e.g. Zambia and Zimbabwe (FAO, 1999).

FIGURE 7
Yield gap at various levels in relation to production factors



Source: Fairhurst and Witt, 2002.

In many developing countries, there is still a very large gap between the economically achievable yield and average yield obtained. Many rice farmers in Asia achieve less than 60 percent of the potential yields (Figure 7). In Figure 7, Y_{max} is the maximum yield potential, Y_{target} is the highest yield that can be obtained through optimal and efficient use of inputs, Y_a is the yield with optimal water and crop management but with the farmer's current nutrient management practices, and Y is the actual yield in the farmer's field. Such a yield gap analysis gives rise to the following considerations (Fairhurst and Witt, 2002):

- Yield gap 1: It is usually uneconomic to attempt to close this yield gap because of the large amounts of inputs required and the high risk of crop failure caused by pests, infection and lodging.
- Yield gap 2: To close this yield gap, it is essential to manage N, based on seasonal plant needs, and follow long-term strategies for other nutrients including P and K.
- Yield gap 3: The greatest benefit from improving nutrient management is found on farms with good crop management and few pest problems. Farmers need to know what factors can be changed to increase productivity (knowledge-based management) and should know that larger yield increases result where several constraints (e.g. pest and disease problems and inappropriate nutrient management) are overcome simultaneously.

Many factors contribute to stagnating or declining yields in spite of farmers' efforts to achieve higher output. Production under adverse conditions faces many natural obstacles, e.g. insufficient and unreliable rainfall, poor or eroded soils, low soil fertility, shortage of irrigation water, crop-damaging and soil-eroding typhoons in humid regions or dust storms in arid regions, and rapidly spreading pests and

TABLE 4
Yields of sorghum and maize on smallholder and commercial farms in Zimbabwe

Crop and farm type	Area	Grain yield	Farmers' yields as % of record yield
	(ha)	(tonnes/ha)	(%)
Sorghum			
Record yield		3.6	
Smallholders	160 000	0.44	12
Commercial farmers	9 000	2.3	64
Maize			
Record yield		5.0	
Smallholder	1 000 000	0.9	18
Commercial farmers	200 000	3.7	74

Source: FAO, 1999.

plant diseases. In addition, there are often economic issues such as high prices for inputs like fertilizers, low produce prices, and poor infrastructure. A combination of some of these factors diminishes the possibility of and incentive for higher yields and production beyond subsistence level.

There are great differences in cereal yield even on similar soils in similar climates. This indicates the significant gaps between usually obtained yields and those obtainable. One example of the impact of expertise and management on yield levels can be seen from the data for Zimbabwe from 1980 to 1996 (Table 4). The yields differed considerably whether obtained in smallholder areas or on commercial farms. There are wide gaps between the average yield and record yield, especially under climate conditions of frequent drought. Smallholders obtained less than 20 percent of the sorghum or maize yields obtained in record years. The better performance of commercial farmers is the result of their greater expertise and better access to inputs. However, even for this group, the long-term average yield is only about 70 percent of that in a record year.

PROBLEMS AND POSSIBILITIES

Two different cases of the problems and possibilities are cited here, one pertaining to SSA and the other to India.

Example of sub-Saharan Africa

With a population of about 500 million, SSA will pose the greatest challenge to food production because of its high population growth rate. This is occurring on top of a decline in available food per capita in recent decades (FAO, 2000a, 2001a, 2001b).

Shortage of productive land

Including dry areas, an estimated 0.4 ha/person was available in 1995. Production increases will have to come mainly from the already cultivated land. In areas receiving satisfactory rainfall, where most people live, the cultivated area was only 0.25 ha/person or less. There is a possibility of a substantial area becoming available (2 ha/person) for cultivation from fallowed land or land under shifting cultivation. However, this will require a massive recapitalization of plant nutrients.

Soil degradation

Soil degradation, particularly that of soil fertility, is a major cause of stagnating or even decreasing yields in some countries. Apart from widespread soil erosion, the major causes are: loss of organic matter resulting in reduced biological activity;

nutrient depletion as a result of erosion, mining or inactivation of nutrient (e.g. sorption of phosphate); and reduced nutrient retention. High levels of soil acidity and aluminium (Al) toxicity are a problem in 30 percent of the area.

The estimated average nutrient depletion in 2000 was about 50 kg of nutrients ($N + P_2O_5 + K_2O$) per year. Without at least a medium level of plant nutrient input, many countries will not be able to meet their food needs, and some may not do so even with high inputs.

Low crop yields

Cereal yields are low at 1 tonne/ha. This is partly the result of soil degradation, a harsh climate, low levels of external nutrient application, and frequent droughts, and partly the result of a lack of economic incentives. Average fertilizer use is only 10 kg/ha of total nutrients (ranging from 0 to 50 kg/ha). Although some areas have shown a distinct yield increase in the last decade, sorghum yields have been stagnant in Burundi, Ethiopia, Ghana, Kenya and Nigeria, and maize yields have been stagnant in Zambia and Zimbabwe. Cassava yields have fallen sharply in Angola and Malawi (FAO, 1999, 2000a).

Regional differences

In the mainly dry semi-arid area, with 250–700 mm rainfall, water supply is the critical factor, as in the Sahel region. Maximum use must be made of the limited rainfall by all kinds of water harvesting techniques. Soils are mainly sandy and of low fertility. The input of minimum nutrients and irrigation of suitable land is often limited by water shortages. Maize and sorghum grain yields range from 0.2 to 1.5 tonnes/ha but much higher yields could be achieved if more water were available.

About 80 percent of the population live in the humid and subhumid agro-ecological zones (700–1 500 mm of rain). In these areas, the main soil problems (besides erosion) are low organic matter and poor biological activity, structural deterioration and nutrient deficiencies. Improvements in plant nutrient supply may start with locally available PR applied to legumes such as *Sesbania*, and adoption of INM. Grain yields of 1–2 tonnes/ha of maize are far lower than they should be. Under these favourable rainfall conditions, grains yields of 3–4 tonnes/ha are possible.

Recent attempts to improve soil fertility have been successful (FAO, 2000a), e.g.:

- Uganda: Soil improvement by farmers association with mulches, manure and fertilizers.
- The United Republic of Tanzania: Water and soil conservation by agroforestry.
- Zambia: Sustainable cropping by replacing grass fallow with legumes plus fertilizer application.
- Burkina Faso: Production increase by use of indigenous PR and more legumes.

To summarize the situation in SSA, there are reasonable prospects of food production, but as indicated in FAO (2000a): "It is necessary to recognize and build upon many indigenous farming systems and soil and management practices that have maintained and sustained agriculture for generations."

Example of India

India is the largest country in South Asia and contains 70 percent of the total regional population. In spite of a rapidly growing population (nine times the growth in area under grains since 1950), it has made significant progress in food production and achieved cereal self-sufficiency with even a sizeable surplus. India, with a population of 1 000 million people, produced 220 kg of cereals per person from an area of 100 million ha in 2000. Such a level of progress has been achieved through intensification and the use of modern production inputs.

Since the green revolution in the 1960s, enormous progress with modern HYVs, irrigation and fertilizer application has been made. Fertilizer consumption rose from almost zero in 1950 to 17 million tonnes of N + P_2O_5 + K_2O in 2000 (Tandon, 2004). This corresponds to an average nutrient application rate of 92 kg/ha, of which 65 percent is N, 25 percent P_2O_5 and 10 percent K_2O. A significant amount of sulphur (S) and zinc (Zn) is also applied.

Average cereal yields are now 2.2 tonnes/ha (2.6 tonnes/ha for rice) and the cropping intensity is 130 percent. Because of the scarcity of land, cereal yields of 3.8 tonnes/ha will be required in order to feed the future population and 500 million domestic animals. Careful use of all kinds of organic nutrient sources would be very desirable given the very large nutrient requirements of Indian agriculture and the persisting gap of 8–10 million tonnes of N + P_2O_5 + K_2O between nutrient additions and removals. It is estimated that 25 percent of the total NPK need could be supplied by organic resources including rural, urban and industrial wastes.

However, the key component will be proper nutrient management with more mineral fertilizers and more balanced nutrient use. This would entail less N and relatively more P and K, which should be supplemented by yield-limiting macronutrients and micronutrients. Even with the present progress, there is still a wide yield gap to be narrowed within safe input limits. Only by more intensive farming backed with INM can 300 million more people be fed by 2020. The alternative of low-input extensive farming would threaten the food security of about 400 million people (FAO/IFPRI, 1998).

These two contrasting scenarios concerning food security can be summarized as follows:

- SSA is the region offering maximum challenges because of rapid population growth and very low cereal yields. The non-utilized yield potential and the substantial fallow land available offers prospects for progress.
- India is a good example of successful past yield increases (and probably future ones) through intensification of agriculture in spite of relatively small additional suitable land reserves.

DEMANDS ON AGRICULTURE FOR PROVIDING FOOD SECURITY

Need for productive and sustainable agriculture

In the foreseeable future, the majority of affordable food must be produced by soil-based agriculture. In order to maintain increased food production, modern agriculture must be very productive and yet sustainable.

There are many definitions of sustainability. The concept of sustainable agriculture set out by FAO (1989) is quite relevant to many countries. It states: "The goal of sustainable agriculture should be to maintain production at levels necessary to meet the increasing aspirations of an expanding world population without degrading the environment." Moreover, "Sustainable agriculture should involve the successful management of resources for agriculture to satisfy changing human need while maintaining or enhancing the quality of the environment and conserving natural resources. No single resource is more important in achieving a sustainable agriculture than the soil which contains essential nutrients, stores the water for plant growth and provides the medium in which plants grow." (FAO, 1989).

According to FAO (1995): "Sustainable agricultural development is the management of the natural resource base in such a manner as to ensure the attainment and continued satisfaction of material human needs for present and future generations. It conserves or increases land capacity to produce agricultural goods, water availability, plant genetic resources, is environmentally non-degrading, technically appropriate, economically viable and socially acceptable."

High-yielding crop production at a sustainable level is based on five factors, which must be integrated efficiently. These factors are:

- productive crops with high-yield potential that are managed properly from seed to harvest;
- fertile soils as the basis for high and sustainable production;
- adequate water supply by rainfall or irrigation;
- adequate nutrient supply for crops, and efficient use of applied nutrients;
- protection of crops against weeds, diseases and pests on the field and post-harvest care in storage.

In principle, sustainable cropping can be carried out at low, medium or high yield levels. The appropriate level is the one that meets the needs and aspirations of the population. Sustainability at a low yield level, termed low input sustainable agriculture (LISA), means a lot of work for small results – a system that many farmers may have no other choice but to use. According to Borlaug (1997): "Most farmers loath to adopt low-input, low-output cropping, because it tends to perpetuate human drudgery and the risk of hunger." The preferred goal is sustainable production at a high level of productivity using adequate inputs. Here, adequate may mean high or medium input depending on the production conditions and targets.

The minimum goal should be sustainable production at medium yield levels. It is likely that most farmers would prefer highly productive sustainable agriculture, a system that makes the use of all inputs and capital worthwhile and results in abundant products and an economic profit. Agriculture should not plunder the soil resource by "exhaustion cropping" for short-term profit, but rather maintain or even improve it for the benefit of future generations. Using banking terminology, agriculture is supposed to live off the interest, not off the inherited capital.

With the results of new research and the extension of new technologies to farmers' fields, considerable progress can be made. However, the optimal utilization of any improved factor requires its integration into the whole production system through a "holistic approach". Individual production factors should not only be improved and applied, but the whole combination of factors must be optimized. This is not a simple task. It requires considerable investment and much expertise.

The five factors listed above are equally important and indispensable for supporting modern agriculture. The yield potential or resistance of crops to diseases may be greatly increased in future, but better crop nutrition with a high nutrient efficiency will remain a central component for productive and sustainable agriculture, and thus for future food security.

Food production adjusted to consumer demands and environmental issues

In most societies, farmers produce food and other agricultural products for a market. Therefore, they must accept market rules and the corresponding economic system, which involves them in a web of special conditions and regulations. However, market demands may be partly contradictory to the demands of the society. Several less desirable developments in modern agriculture are not just the result of modern technology as such but of conflicting demands of urban consumers, mostly in the developed countries, who are politically dominant and increasingly determine the basic rules for farmers. Three examples of this are:

- Urban consumers want food to be cheap but many of them dislike the consequences of "mass production" of so-called "industrial" agriculture. For example, in order to produce cheap meat, farmers are forced to keep large numbers of pigs in sheds where the wastes are collected as slurry instead of straw containing farmyard manure (FYM). Slurry was practically unknown in Europe 50 years ago, but is now the dominant form of animal manure and probably the most important source of plant nutrient losses from agriculture to the environment. This represents a "consumer-driven" undesirable development in modern agriculture.
- Many urban consumers, largely for supposed health reasons, prefer so-called "natural" food, supposedly produced by low-input production, but also want much land left to natural vegetation in order to preserve biodiversity. So-called "organic" farming, being connected with nostalgic reminiscences, seems to guarantee healthy and uncontaminated food from crops growing without "chemicals" and from "happy" farm animals on "natural" green pastures. However, low-input production, without actually producing better food, is not only more costly, but requires more than twice as much land for cropping. Therefore, this demand comes into conflict with the demand of urban populations for large recreational areas with natural parks, etc.

- Urban consumers return their partly contaminated waste materials to agriculture, but tend to criticize farmers for selling "contaminated" food to urban markets. However, while the enormous amounts of waste materials need to be recycled as cheaply available nutrient sources, many of these products are contaminated by inorganic and/or organic toxic substances, which may damage soil fertility or food quality. This problem needs to be solved at the expense of urban populations who are causing this problem, otherwise farmers will be reluctant or even unwilling to use such urban wastes.

From these examples, it seems that urban consumers, most of them lacking a basic understanding of agricultural production, can put a great strain on agriculture with contradictory demands. Farmers have to react to conflicting requests, and in any case, should not be held responsible for the consequences of recycling contaminated urban waste products.

For the goal of food security, farmers should not be made responsible for the results of conflicting demands of urban consumers who set the principles and laws with little regard for the unique rules of basic agriculture production. Much work is needed in laying down the ground rules for the on-farm recycling of wastes. Steps should be taken to ensure that urban wastes processed for recycling meet appropriate quality standards so that their use on farmland does not harm the land, produce, waterbodies, people or the environment.

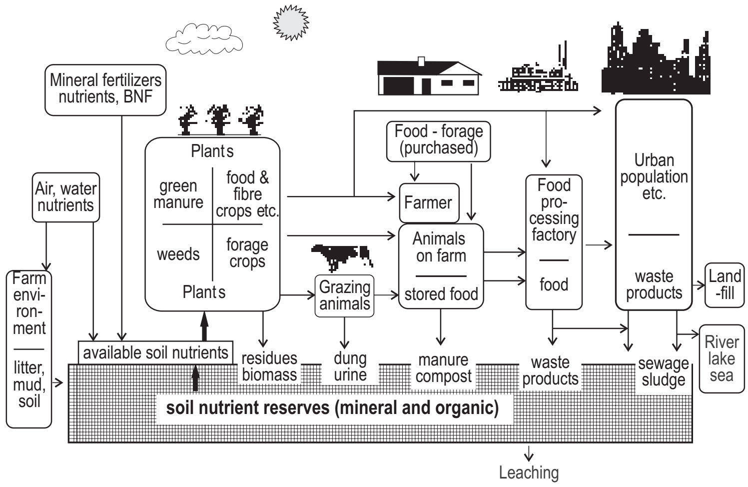
NUTRIENTS IN PRODUCTION AND CONSUMPTION CYCLES AND NUTRIENT TRANSFERS

All harvested crops remove plant nutrients from the soil. Whether used for food, feed or as industrial raw materials, the various crop products are often consumed far away from the production sites, some times thousands of kilometres away in another country. When crop products are moved, the nutrients contained in them are also transported. This implies a loss of nutrients for the production area and a gain for the area where these are finally utilized. Although soils gain as well as lose nutrients, agricultural production and food security is threatened whenever the nutrients removed or lost are not replenished adequately. In the end, it is the balance between the amounts gained and the amounts lost that determines whether the soil nutrient status is being depleted, maintained or improved, and this in turn determines the productivity level that a soil can sustain.

Whether at the farm level or across national boundaries, nutrient cycling takes place to varying extents. Quite often, where nutrients are circulating in small or large cycles, taken up and partly transformed by plants, microbes, animals or humans, they reappear in waste materials, which can again serve as nutrient sources (Figure 8).

Such cycles operate continuously in soils at various levels. Nature, which operates these cycles, does not discriminate between organic or mineral forms of nutrient and allows both forms to enter and leave the same cycle. However, intersite nutrient transfers bring about different types of changes in the nutrient balance than do normal nutrient cycles.

FIGURE 8
Plant nutrients in production and consumption cycles



Source: Finck, 1992.

Natural nutrient transfers

A steady flow of nutrients occurs naturally with surface water or groundwater movement in hilly and mountainous areas as part of the natural erosion process, even under natural vegetation cover. The annual losses of nutrients in the soil solution from hilly parts of the landscape are often relatively small as are the gains for the low-lying land. However, the amount of nutrients transferred in solid form by soil erosion can be considerable. Over geological time, this transfer has produced impoverished hilly areas and many fertile alluvial soils in river basins that now represent the best agricultural lands in the world. Where this process is accelerated by human-induced soil erosion, it can lead to serious declines in soil fertility in hilly areas and to excessive losses of nutrients into water.

The problem of natural nutrient transfers can be considerable in the plains as well. This is caused primarily by the movement of nutrient-rich surface soils through wind and water erosion. In India, about 5 300 million tonnes of soil are estimated to be displaced annually through water erosion alone, resulting in a movement of 8 million tonnes of N + P_2O_5 + K_2O (Prasad and Biswas, 2000). These cannot be considered real losses because a significant proportion of this tonnage is intersite transfers. Such a large transfer of plant nutrients is close to one-third of the nutrients removed by harvested crops and nearly half of the amounts added through fertilizers (Tandon, 2004).

On-farm nutrient cycles

The nutrient cycles in the field or on the farm are not closed. Some nutrients are removed (exported) from the field or farm with food, feed and raw materials, others are just lost. At the same time, a field also gains nutrients through biological nitrogen fixation (BNF) and the addition of fertilizers and manures. Some losses are inherent to crop production because some production factors cannot be controlled. However, many losses can be avoided by more efficient management and recycling. In order to remain sustainable, nutrient cycles need some input from soil reserves and/or from external nutrient sources. An indicator of nutrient status is the input/output balance at the field or farm level. With higher productivity, the amount of circulating nutrients usually increases as a result of increased nutrient input as well as output in order to sustain the process at a high level of productivity. In areas where groundwaters are pumped for irrigation, some of the leached nutrient can return and re-enter the cycle as an input.

Regional nutrient transfer

Many nutrients leave the farm or the village and are transferred to urban areas. These transfers could be a few kilometres away to the nearest town or even several hundred kilometres away from a food-surplus to a food-deficit region within the same country. Ideally, they should be completely recycled to agricultural soils. However, in most cities, large amounts of nutrients are deposited into landfills or into the sea, which is a wasteful procedure, especially for nutrients in limited supply, e.g. phosphate. The transfer of phosphate to cities is used as an example to demonstrate the magnitude of this problem. Humans need 1.0–1.5 g of P per day, which translates into a supply of about 1.7 g of P per day. Therefore, a city of 1 million people requires 1.7 tonnes of P per day or 620 tonnes of P per year (1 400 tonnes of P_2O_5). As phosphate is used in human metabolism, but not destroyed, a large proportion of the P intake amount appears in solid or liquid wastes. Ideally, these should be recycled.

However, P recovery from city wastes varies from 10 to 80 percent depending on the sophistication of the recycling systems. Some urban areas have exemplary P-recovery systems with precipitation of Fe or Al phosphate from wastewaters, and agricultural use of these mineral phosphates as nutrient sources. The rate of recycling usually decreases with increasing size of the settlement. Many cities are proud of their sewage disposal system, which often disposes of biologically treated sewage water into rivers or into the sea. This action of just disposing of waste materials is not the best solution. It means an enormous loss of plant nutrients with secondary effects of pollution, health hazards and eutrophication.

The main obstacles to complete recycling of plant nutrients from urban areas are the unwanted side-effects that urban waste products can have on farmers fields, even where they are composted. Therefore, knowledgeable farmers are increasingly reluctant to apply composted sewage or garbage as nutrient sources, even if offered free of charge, because of the problems of toxic heavy metals and possibly toxic organic substances. With environmental laws in some areas becoming more severe, farmers suspect that the critical limits for soil contamination might be decreased, thus putting otherwise fertile land out of production.

In addition, farmers dislike being accused by urban people of "poisoning" the soil and so decreasing food quality while at the same time using or rather misusing their fields to dispose of urban wastes. Recycling of urban wastes in many developing countries does not exist beyond dumping. Any recycling is rather casual because of a lack of quality standards and adequate information for producers and consumers. Farmers near urban areas are sometimes known to willingly use urban wastes, sewage sludge, etc. for vegetable production meant for sale but do not use these wastes on the small patch of land reserved for growing crops for home consumption.

In the future, ever-increasing urbanization will result in an enormous nutrient transfer into the cities. Hence, steps must be taken to enhance the recycling of plant nutrients. This can be achieved through the composting of urban wastes and utilization of sewage as well as slaughterhouse waste for manuring. At the same time, quality standards must be established and enforced, supplemented by proper education at all levels along the recycling chain, on a continuous basis.

International nutrient transfer

The export of food and feed results in considerable amounts of nutrients being transferred to other countries, or even other continents, without being recycled. Some developed countries import enormous amounts of plant nutrients with feed for animals. Global nutrient transfer partly results in a paradoxical situation where plant nutrients are mined from poor soils in developing countries and added to already fertile soils in developed areas. The reverse is the case where food is imported by developing countries to meet shortages created by low local production.

Nutrient exports

The export of agricultural products results in an unnoticed export of plant nutrients and, thus, a loss from the national nutrient balance. These nutrient exports to other countries can reach substantial amounts (Table 5).

About 15 kg of N, 5–6 kg of P_2O_5 and 5–6 kg of K_2O are exported from the farm with every tonne of cereal. Thailand and Viet Nam together have a net export through cereals of about 150 000 tonnes of N and 60 000 tonnes each of

TABLE 5
Examples of plant nutrients exported and imported through cereals, 1999

Movement	Country	Commodity	Nutrients (1 000 tonnes) N	P_2O_5	K_2O
Export	Developing countries	Cereals	740	300	300
	Thailand	Cereals	90	36	36
	Viet Nam	Cereals	57	23	23
	Zimbabwe	Cereals	3.25	1.3	1.3
Import	Netherlands	Cereals[1]	100	40	40
	Germany	Cereals[1]	45	18	18

[1] Imported mainly for feed.

phosphate and potash. The developing countries as a whole have a loss of about 1.3 million tonnes of nutrients, mainly through cereal exports. The amounts are shown in terms of NPK only as an example. In reality, all nutrients present in the exported produce are also moved across national boundaries. Such exports cause a considerable loss of nutrients, which are largely obtained by nutrient mining of often already poor soils and are not compensated for by imports.

On the other hand, as long as this transfer of nutrients with agricultural products is, or can be, compensated for by re-imports of mineral fertilizers, the nutrient loss from the developing countries will not be a serious problem. However, it is necessary to consider the overall economic and environmental aspects of importing fertilizer nutrients and at what level of efficiency these will be used for crop production. In any case, nutrients exported through crops represent net removals, while 2–4 units of fertilizer nutrients are needed for every unit of nutrient contained in the crops exported.

As trade barriers for the export of agricultural produce from developing countries are removed, the issue of international nutrient transfers will need re-examining. In any case, nutrients exported through crop products cannot be equated with nutrients imported through fertilizers on a 1:1 basis. This is because a fraction of the fertilizer nutrients ends up in the exported product. In addition, it cannot be assumed that when fertilizers are imported by a country, these are used in the areas that produced the exportable surplus. This is one reason why macrolevel nutrient balances fail to provide insights into nutrient balances at the microlevel.

Import of nutrients

The Netherlands and Germany import about 150 000 tonnes of N and 60 000 tonnes each of phosphate and potash in grains imported for animal feed. After consumption, the animal wastes are used as nutrient sources for manuring the fields. Often, animal slurry is added to soils that are already well supplied with available P and K in these countries. This could be because the farmland is easily accessible for the disposal of slurry.

Many developed countries with high animal production produce sufficient feedstuff from their own agriculture but import substantial amounts of feedstuff because of cheaper prices. For the Netherlands, these imports are outstandingly high, and in the cases of P and K have been estimated to represent about two-thirds of total fertilizer imports (Cooke, 1982). Food-deficit developing countries also import plant nutrient whenever they import food grains or other farm produce (grain legumes, oilseeds and sugar) whether from developed countries or from other developing countries.

In such countries, it makes sound agro-economical and ecological sense to import fertilizers and develop their agricultural production capability rather than import food grains or other "finished" crop products. By putting the plant nutrient to work, they can make value-added products out of their abundant supplies of sunlight, air, carbon dioxide (CO_2)and human labour. International nutrient transfer is a subject that will become increasingly relevant and also provide a basis for developing the most effective strategies of international trade of inputs as well as output. Towards this end, the optimization of plant nutrients has a role to play because by maximizing the efficiency of production inputs, unit-product cost can be reduced and farm produce made more competitive. At the same time, national farm policies may be needed that ensure that the highly productive agricultural soils are replenished with adequate nutrients in order to sustain their productivity. These are also the areas where crop production skills have reached a satisfactory level and where efficient use of applied nutrients can be expected. All these factors will contribute towards increasing agricultural production and ensuring food security.

Chapter 3
Plant nutrients and basics of plant nutrition

Plants convert light energy into biomass through photosynthesis and produce various products of economic value (grain, fibre, tubers, fruits, vegetables and fodder) among others. To do this, plants need sufficient light, suitable temperature, substances such as water, CO_2, oxygen, and a number of nutrients. The survival and well-being of humans and animals depends on plant production, which in turn depends heavily on the availability of mineral and other nutrients. This is why plants and animals (including humans) have several essential nutrients in common.

Like all organisms, higher green plants need nutrients for their growth and development. Nutrients are indispensable as plant constituents, for biochemical reactions, and for the production of organic materials referred to as photosynthates (carbohydrates, proteins, fats, vitamins, etc.) by photosynthesis. In agriculture (including horticulture), optimal crop nutrition is an important prerequisite for obtaining high yields and good-quality produce. The nutrients required are obtained by plants both from soil reserves and external nutrient sources (fertilizers, organic manures, the atmosphere, etc). Almost all of the 90 natural elements can be found in green plants although most of them have no function (e.g. the heavy metal gold).

PLANT NUTRIENTS

Essential plant nutrients

A total of only 16 elements are essential for the growth and full development of higher green plants according to the criteria laid down by Arnon and Stout (1939). These criteria are:

- A deficiency of an essential nutrient makes it impossible for the plant to complete the vegetative or reproductive stage of its life cycle.
- Such deficiency is specific to the element in question and can be prevented or corrected only by supplying this element.
- The element is involved directly in the nutrition of the plant quite apart from its possible effects in correcting some unfavourable microbiological or chemical condition of the soil or other culture medium.

The essentiality of most micronutrients for higher plants was established between 1922 and 1954. The essentiality of nickel (Ni) was established in 1987 by Brown et al, although there is no unanimity among the scientists as to whether Ni is essential or beneficial. However, this list may not be considered as final and it is probable that more elements may prove to be essential in future.

TABLE 6
Essential plant nutrients, forms taken up and their typical concentration in plants

Nutrient (symbol)	Essentiality established by	Forms absorbed	Typical concentration in plant dry matter
Macronutrients			
Nitrogen (N)	de Saussure (1804)	NH_4^+, NO_3	1.5%
Phosphorus (P, P_2O_5[1])	Sprengel (1839)	$H_2PO_4^-$, HPO_4^{2-}	0.1–0.4%
Potassium (K, K_2O[1])	Sprengel (1839)	K^+	1–5%
Sulphur (S)	Salm-Horstmann (1851)	SO_4^{2-}	0.1–0.4%
Calcium (Ca)	Sprengel (1839)	Ca^{2+}	0.2–1.0%
Magnesium (Mg)	Sprengel (1839)	Mg^{2+}	0.1–0.4%
Micronutrients			
Boron (B)	Warington (1923)	H_3BO_3, $H_2BO_3^-$	6–60 µg/g (ppm[2])
Iron (Fe)	Gris (1943)	Fe^{2+}	50–250 µg/g (ppm)
Manganese (Mn)	McHargue (1922)	Mn^{2+}	20–500 µg/g (ppm)
Copper (Cu)	Sommer, Lipman (1931)	Cu^+, Cu^{2+}	5–20 µg/g (ppm)
Zinc (Zn)	Sommer, Lipman (1931)	Zn^{2+}	21–150 µg/g (ppm)
Molybdenum (Mo)	Arnon & Stout (1939)	MoO_4^{2-}	below 1 µg/g (ppm)
Chlorine (Cl)	Broyer *et al.,* (1954)	Cl^-	0.2–2 percent

Notes:
[1] Oxide forms are used in extension and trade.
[2] ppm = parts per million = mg/kg = µg/g; 10 000 ppm = 1 percent.

Out of these 16 elements, carbon (C) and oxygen are obtained from the gas CO_2, and hydrogen (H) is obtained from water (H_2O). These three elements are required in large quantities for the production of plant constituents such as cellulose or starch. The other 13 elements are called mineral nutrients because they are taken up in mineral (inorganic) forms. They are traditionally divided into two groups, macronutrients and micronutrients, according to the amounts required. Regardless of the amount required, physiologically, all of them are equally important. The 13 mineral elements are taken up by plants in specific chemical forms (Table 6) regardless of their source.

Oxygen, C and H make up 95 percent of plant biomass, and the remaining 5 percent is made up by all other elements. The difference in plant concentration between macronutrients and micronutrients is enormous. The relative contents of N and molybdenum (Mo) in plants is in the ratio of 10 000:1. Plants need about 40 times more magnesium (Mg) than Fe. These examples indicate the significant difference between macronutrients and micronutrients. Chapter 6 provides more detailed on nutrient concentration in crops and crop products.

Beneficial nutrients

Several elements other than the essential nutrients have beneficial functions in plants. Although not essential (as the plant can live without them), beneficial nutrients can improve the growth of some crops in some respects. Some of these nutrients can be of great practical importance and may require external addition:

- Nickel (Ni): a part of enzyme urease for breaking urea in the soil, imparts useful role in disease resistance and seed development.
- Sodium (Na): for beets, partly able to replace K (uptake as Na^+).

- Cobalt (Co): for N fixation in legumes and for other plants (uptake as Co^{2+}).
- Silicon (Si): for stalk stability of cereals particularly rice (uptake as silicate anion).
- Aluminium (Al): for tea plants (uptake as Al^{3+} or similar forms).

Other important nutrients

As humans and domestic animals require several nutrients in addition to those required by plants, these additional nutrients should also be considered in food or feed production, and their deficiencies corrected by appropriate inputs. In addition to plant nutrients, the elements essential for humans and domestic animals are: Cobalt (Co), selenium (Se), chromium (Cr) and iodine (I).

NUTRIENTS – THEIR FUNCTIONS, MOBILITY IN PLANTS AND DEFICIENCY/ TOXICITY SYMPTOMS

Some knowledge of the properties and functions of plant nutrients is helpful for their efficient management and, thus, for good plant growth and high yields. Available nutrients in the soil solution can be taken up by the roots, transported to the leaves and used according to their functions in plant metabolism.

Nutrient ions are of extremely small size, i.e. like atoms. For example, there are more than 100 000 million K^+ cations within a single leaf cell and more than 1 000 000 molybdate anions, the micronutrient required in the smallest amount. In general, N and K make up about 80 percent of the total mineral nutrients in plants; P, S, Ca and Mg together constitute 19 percent, while all the micronutrients together constitute less than 1 percent.

Most plant nutrients are taken up as positively or negatively charged ions (cations and anions, respectively) from the soil solution. However, some nutrients may be taken up as entire molecules, e.g. boric acid and amino acids, or organic complexes such as metal chelates and to a very small extent urea. Whether the original sources of nutrient ions in the soil solution are from organic substances or inorganic fertilizers, ultimately, the plants absorb them only in mineral forms.

Plants exhibit many shades of greenness but a medium to dark green colour is usually considered a sign of good health and active growth. Chlorosis or yellowing of leaf colour can be a sign of a marginal deficiency and is often associated with retarded growth. Chlorosis is a light green or rather yellowish discoloration of the whole or parts of the leaf caused by a lower content of chlorophyll. Because the cells remain largely intact, the chlorotic symptoms are reversible, i.e. leaves can become green again after the missing nutrient (responsible for chlorophyll formation) is added. A severe deficiency results in death of the tissue (necrosis). Necrosis is a brownish discoloration caused by decaying tissue, which is destroyed irreversibly. Necrotic leaves cannot be recovered by addition of the missing nutrient, but the plant may survive by forming new leaves.

Deficiency symptoms can serve as a guide for diagnosing limiting nutrients and the need for corrective measures. However, chlorotic and necrotic leaves might also result from the toxic effects of nutrients, pollution and also from disease and insect attacks. Therefore, confirmation of the cause is important before corrective measures are taken.

Nitrogen

N is the most abundant mineral nutrient in plants. It constitutes 2–4 percent of plant dry matter. Apart from the process of N fixation that occurs in legumes, plants absorb N either as the nitrate ion (NO_3^-) or the ammonium ion (NH_4^+). N is a part of the chlorophyll (the green pigment in leaves) and is an essential constituent of all proteins. It is responsible for the dark green colour of stem and leaves, vigorous growth, branching/tillering, leaf production, size enlargement, and yield formation.

Absorbed N is transported through the xylem (in stem) to the leaf canopy as nitrate ions, or it may be reduced in the root region and transported in an organic form, such as amino acids or amides. N is mobile in the phloem (the plant tissue through which the sap containing dissolved food materials passes downwards to the stem, roots, etc.); as such, it can be re-translocated from older to younger leaves under N deficiency and translocated from leaves to the developing seed or fruit. The principal organic forms of N in phloem sap are amides, amino acids and ureides. Nitrate and ammonium ions are not present in this sap.

N deficiency in plants results in a marked reduction in growth rate. N-deficient plants have a short and spindly appearance. Tillering is poor, and leaf area is small. As N is a constituent of chlorophyll, its deficiency appears as a yellowing or chlorosis of the leaves. This yellowness usually appears first on the lower leaves while upper leaves remain green as they receive some N from older leaves. In a case of severe deficiency, leaves turn brown and die. As a result, crop yield and protein content are reduced (percent N in seed × 6.25 = percent protein content).

The effects of N toxicity are less evident than those of its deficiency. They include prolonged growing (vegetative) period and delayed crop maturity. High NH_4^+ in solution can be toxic to plant growth, particularly where the solution is alkaline. The toxicity results from ammonia (NH_3), which is able to diffuse through plant membranes and interfere with plant metabolism. The potential hydrogen (pH – negative log of H^+ concentration) determines the balance between NH_3 and NH_4^+.

Phosphorus

P is much less abundant in plants (as compared with N and K) having a concentration of about one-fifth to one-tenth that of N in plant dry matter. P is absorbed as the orthophosphate ion (either as $H_2PO_4^-$ or HPO_4^{2-}) depending on soil pH. As the soil pH increases, the relative proportion of $H_2PO_4^-$ decreases and that of HPO_4^{2-} increases. P is essential for growth, cell division, root lengthening, seed and fruit development, and early ripening. It is a part of several compounds including oils and amino acids. The P compounds adenosine diphosphate (ADP) and adenosine triphosphate (ATP) act as energy carriers within the plants.

P is readily mobile within the plant (unlike in the soil) both in the xylem and phloem tissues. When the plant faces P shortage (stress), P from the old leaves is readily translocated to young tissue. With such a mobile element, the pattern of redistribution seems to be determined by the properties of the source (old leaves, and stems) and the sink (shoot tip, root tip, expanding leaves and later into the developing seed).

Plant growth is markedly restricted under P deficiency, which retards growth, tillering and root development and delays ripening. The deficiency symptoms usually start on older leaves. A bluish-green to reddish colour develops, which can lead to bronze tints and red colour. A shortage of inorganic phosphate in the chloroplast reduces photosynthesis. Because ribonucleic acid (RNA) synthesis is reduced, protein synthesis is also reduced. A decreased shoot/root ratio is a feature of P deficiency, as is the overall lower growth of tops.

Extremely high levels of P can result in toxicity symptoms. These generally manifest as a watery edge on the leaf tissue, which subsequently becomes necrotic. In very severe cases, P toxicity can result in the death of the plant.

Potassium

K is the second most abundant mineral nutrient in plants after N. It is 4–6 times more abundant than the macronutrients P, Ca, Mg and S. K is absorbed as the monovalent cation K^+ and it is mobile in the phloem tissue of the plants. K is involved in the working of more than 60 enzymes, in photosynthesis and the movement of its products (photosynthates) to storage organs (seeds, tubers, roots and fruits), water economy and providing resistance against a number of pests, diseases and stresses (frost and drought). It plays a role in regulating stomatal opening and, therefore, in the internal water relations of plants.

The general symptom of K deficiency is chlorosis along the leaf boundary followed by scorching and browning of tips of older leaves. The affected area moves inwards as the severity of deficiency increases. K-deficiency symptoms show on the older tissues because of the mobility of K. Affected plants are generally stunted and have shortened internodes. Such plants have: slow and stunted growth; weak stalks and susceptibility to lodging; greater incidence of pests and diseases; low yield; shrivelled grains; and, in general, poor crop quality. Slow plant growth can be accompanied by a higher rate of respiration, which means a wasteful consumption of water per unit of dry matter produced. K-deficient plants may lose control over the rate of transpiration and suffer from internal drought.

Calcium

Calcium (Ca) ranks with Mg, P and S in the group of least abundant macronutrients in plants. It is absorbed by plant roots as the divalent cation Ca^{2+}. Ca is a part of the architecture of cell walls and membranes. It is involved in cell division, growth, root lengthening and activation or inhibition of enzymes. Ca is immobile in the phloem.

Ca deficiency is seen first on growing tips and the youngest leaves. This is the case with all nutrients that are not very mobile in the plants. The Ca-deficiency problems are often related to the inability of Ca to be transported in the phloem. The problems occur in organs that do not transpire readily, i.e. large, fleshy developing fruits. Ca-deficient leaves become small, distorted, cup-shaped, crinkled and dark green. They cease growing, become disorganized, twisted and, under severe deficiency, die. Although all growing points are sensitive to Ca deficiency, those of the roots are affected more severely. Groundnut shells may be hollow or poorly filled as a result of incomplete kernel development.

Magnesium

Mg ranks with Ca, P and S in the group of least abundant macronutrients in plants. Plants take up Mg in the form of Mg^{2+}. Mg occupies the centre-spot in the chlorophyll molecule and, thus, is vital for photosynthesis. It is associated with the activation of enzymes, energy transfer, maintenance of electrical balance, production of proteins, metabolism of carbohydrates, etc. Mg is mobile within the plants.

As Mg is readily translocated from older to younger plant parts, its deficiency symptoms first appear in the older parts of the plant. A typical symptom of Mg deficiency is the interveinal chlorosis of older leaves in which the veins remain green but the area between them turns yellow. As the deficiency becomes more severe, the leaf tissue becomes uniformly pale, then brown and necrotic. Leaves are small and break easily (brittle). Twigs become weak and leaves drop early. However, the variety of symptoms in different plant species is so great that their generalized description is more difficult in case of Mg than for other nutrients.

Sulphur

S is required by crops in amounts comparable with P. The normal total S concentration in vegetative tissue is 0.12–0.35 percent and the total N/total S ratio is about 15. Plant roots absorb S primarily as the sulphate ion (SO_4^{2-}). However, it is possible for plants to absorb sulphur dioxide (SO_2) gas from the atmosphere at low concentrations.

S is a part of amino acids cysteine, cystine and methionine. Hence, it is essential for protein production. S is involved in the formation of chlorophyll and in the activation of enzymes. It is a part of the vitamins biotin and thiamine (B_1), and it is needed for the formation of mustard oils, and the sulphydryl linkages that are the source of pungency in onion, oils, etc.

S moves upwards in the plant as inorganic sulphate anion (SO_4^{2-}). Under low S conditions. mobility is low as the S in structural compounds cannot be translocated. As the S status of the plant rises, so does its mobility. This pattern of mobility means that in plants with adequate S, sulphate is preferentially translocated to young, actively growing leaves. As the supply of S becomes more limiting, young leaves lack S and, hence, show deficiency symptoms.

In many ways, S deficiency resembles that of N. It starts with the appearance of pale yellow or light-green leaves. Unlike N deficiency, S-deficiency symptoms in most cases appear first on the younger leaves, and are present even after N application. Plants deficient in S are small and spindly with short and slender stalks. Their growth is retarded, and maturity in cereals is delayed. Nodulation in legumes is poor and N fixation is reduced. Fruits often do not mature fully and remain light green in colour. Oilseed crops deficient in S produce a low yield and the seeds have less oil in them.

S toxicity can occur under highly reduced conditions, possibly as a result of sulphide (H_2S) injury. Most plants are susceptible to high levels of atmospheric SO_2. Normal SO_2 concentrations range from 0.1 to 0.2 mg SO_2/m^3, and toxicity symptoms are observed when these exceed 0.6 mg SO_2/m^3. S-toxicity symptoms appear as necrotic spots on leaves, which then spread over the whole leaf.

Boron

Boron (B) is probably taken up by plants as the undissociated boric acid (H_3BO_3). It appears that much of the B uptake mainly follows water flow through roots. B in a plant is like the mortar in a brick wall, the bricks being the cells of growing parts such as tips (meristems). Key roles of B relate to: (i) membrane integrity and cell-wall development, which affect permeability, cell division and extension; and (ii) pollen tube growth, which affects seed/fruit set and, hence, yield. B is relatively immobile in plants and, frequently, the B content increases from the lower to the upper parts of plants.

B deficiency usually appears on the growing points of roots, shoots and youngest leaves. Young leaves are deformed and arranged in the form of a rosette. There may be cracking and cork formation in the stalks, stem and fruits; thickening of stem and leaves; shortened internodes, withering or dying of growing points and reduced bud, flower and seed production. Other symptoms are: premature seed drop or fruit drop; crown and heart rot in sugar beet; hen- and chicken-type bunches in grapes; barren cobs in maize; hollow heart in groundnut; unsatisfactory pollination; and poor translocation of assimilates. Death of the growing tip leads to sprouting of auxiliary meristem and a bushy broom-type growth. Roots become thick, slimy and have brownish necrotic spots.

B toxicity can arise under excessive B application, in arid or semi-arid areas, and where irrigation water is rich in B content (more than 1–2 ppm B). B-toxicity symptoms are yellowing of the leaf tip followed by gradual necrosis of the tip and leaf margins, which spreads towards the midrib (central vein). Leaves become scorched and may drop early.

Chlorine

Chlorine (Cl) is absorbed as the chloride anion (Cl^-). It is thought to be involved in the production of oxygen during photosynthesis, in raising cell osmotic pressure and in maintaining tissue hydration. Some workers consider it essential only for palm and kiwi fruit. Deficiency of Cl leads to chlorosis in younger leaves and overall wilting as a consequence of the possible effect on transpiration. Cl-toxicity symptoms are: burning of the leaf tips or margins; bronzing; premature yellowing; leaf fall; and poor burning quality of tobacco.

Copper

Copper (Cu) is taken up as Cu^{2+}. Its uptake appears to be a metabolically mediated process. However, Cu uptake is largely independent of competitive effects and relates primarily to the levels of available Cu in the soil. Cu is involved in chlorophyll formation and is a part of several enzymes such as cytochrome oxidase. As much as 70 percent of the Cu in plants may be present in the chlorophyll, largely bound to chloroplasts. It participates in lignin formation, protein and carbohydrate metabolism, and is possibly required for symbiotic N fixation. Cu is a part of plastocyanin, which forms a link in the electron transport chain involved in photosynthesis. Cu is not readily mobile in the plant and its movement is strongly dependent on the Cu status of the plant.

Cu-deficiency symptoms are first visible in the form of narrow, twisted leaves and pale white shoot tips. At maturity, panicles/ears are poorly filled and even empty where the deficiency is severe. In fruit trees, dieback of the terminal growth can occur. In maize, yellowing between leaf veins takes place, while in citrus the leaves appear mottled and there is dieback of new twigs.

Cu-toxicity symptoms are more variable with species and less established than its deficiency symptoms. Excess Cu induces Fe deficiency and, therefore, chlorosis is a common symptom.

Iron

Fe is absorbed by plant roots as Fe^{2+}, and to a lesser extent as Fe chelates. For efficient utilization of chelated Fe, separation between Fe and the organic ligand has to take place at the root surface, after the reduction of Fe^{3+} to Fe^{2+}. Absorbed Fe is immobile in the phloem. Fe is generally the most abundant of the micronutrients with a dry-matter concentration of about 100 µg/g (ppm). It plays a role in the synthesis of chlorophyll, carbohydrate production, cell respiration, chemical reduction of nitrate and sulphate, and in N assimilation.

Fe deficiency begins to appear on younger leaves first. Otherwise, its deficiency symptoms are somewhat similar to those of Mn, as both Fe and Mn lead to failure in chlorophyll production. Yellowing of the interveinal areas of leaves (commonly referred to as iron chlorosis) occurs. In severe deficiency, leaves become almost pale white because of the loss of chlorophyll. In cereals, alternate yellow and green stripes along the length of the leaf blade may be observed. Complete leaf fall can occur and shoots can die.

Fe toxicity of rice is known as bronzing. In this disorder, the leaves are first covered by tiny brown spots that develop into a uniform brown colour. It can be a problem in highly reduced rice soils as flooding may increase the levels of soluble Fe from 0.1 to 50–100 µg/g Fe within a few weeks. It can also be a problem in highly weathered, lowland acid soils.

Manganese

Manganese (Mn) is taken up by plants as the divalent ion Mn^{2+}. It is known to activate several enzymes and functions as an auto-catalyst. It is essential for splitting the water molecule during photosynthesis. It has certain properties similar to Mg. It is also important in N metabolism and in CO_2 assimilation. Like Fe, it is generally immobile in the phloem.

Mn-deficiency symptoms resemble those of Fe and Mg deficiency where interveinal chlorosis occurs in the leaves. However, Mn-deficiency symptoms are first visible on the younger leaves whereas in Mg deficiency, the older leaves are affected first. Mn deficiency in oats is characterized by "grey-speck" where the leaf blade develops grey lesions but the tip remains green, the base dies and the panicle may be empty. In dicots (e.g. legumes), younger leaves develop chlorotic patches between the veins (somewhat resembling Mg deficiency).

Mn-toxicity symptoms lead to the development of brown spots, mainly on older leaves and uneven green colour. Some disorders caused by Mn toxicity are: crinkle leaf spot in cotton; stem streak; necrosis of potato; and internal bark necrosis of apple trees.

Molybdenum

Mo is absorbed as the molybdate anion MoO_4^{2-} and its uptake is controlled metabolically. Mo is involved in several enzyme systems, particularly nitrate reductase, which is needed for the reduction of nitrate, and nitrogenase, which is involved in BNF. Thus, it is involved directly in protein synthesis and N fixation by legumes. Mo appears to be moderately mobile in the plant. This is suggested by the relatively high levels of Mo in seeds, and because deficiency symptoms appear in the middle and older leaves.

Mo deficiency in legumes can resemble N deficiency because of its role in N fixation. Mo deficiency can cause marginal scorching and rolling or cupping of leaves and yellowing and stunting in plants. Yellow spot disease in citrus and whip tail in cauliflower are commonly associated with Mo deficiency.

Fodders containing more than 5 µg/g Mo in the dry matter are suspected to contain toxic levels of Mo for grazing animals (associated with the disease molybdenosis).

Zinc

Zn is taken up as the divalent cation Zn^{2+}. Early work suggested that Zn uptake was passive, but more recent work indicates that it is active (energy-dependent). Zn is required directly or indirectly by several enzymes systems, auxins and in protein synthesis, seed production and rate of maturity. Zn is believed to promote RNA synthesis, which in turn is needed for protein production. The mobility of Zn is low. The rate of Zn mobility to younger tissue is particularly depressed in Zn-deficient plants.

Common symptoms of Zn deficiency are: stunted plant growth; poor tillering; development of light green, yellowish, bleached spots; chlorotic bands on either side of the midrib in monocots (particularly maize); brown rusty spots on leaves in some crops, which in acute Zn deficiency as in rice may cover the lower leaves; and in fruit trees the shoots may fail to extend and the small leaves may bunch together at the tip in a rosette-type cluster. Little-leaf condition is also a common symptom. Internodes are short. Flowering, fruiting and maturity can be delayed. Shoots may die off and leaves can fall prematurely. Deficiency symptoms are not the same in all plants.

Zn toxicity can result in reduction in root growth and leaf expansion followed by chlorosis. It is generally associated with tissue concentrations greater than 200 µg/g Zn.

BENEFICIAL ELEMENTS

Nickel

Ni is a part of the enzyme urease, which breaks down urea in the soil. It also plays a role in imparting disease resistance and is considered essential for seed development. Information on various aspects of Ni as a micronutrient is gradually becoming available.

Silicon

Si is taken up as the undissociated $Si(OH)_4$ monosilicic acid. The prevalent form of Si in plants is silica gel in the form of hydrated amorphous silica (SiO_2 in H_2O), or polymerized silicic acid, which is immobile in the plant.

The beneficial effects of Si on plants include increases in yield that can result from increasing leaf erectness, decreasing susceptibility to lodging, decreasing incidence to fungal infections, and prevention of Mn and/or Fe toxicity. Thus, Si is able to counteract the effects of high N, which tend to increase lodging.

In lowland or wetland rice that is low in Si, vegetative growth and grain production is reduced severely and deficiency symptoms such as necrosis of the mature leaves and wilting can occur. Similarly, sugar cane suffers growth reduction under conditions of low Si availability.

Cobalt

Co is taken up as the divalent cation Co^{2+}. It is essential for N-fixing micro-organisms, irrespective of whether they are free-living or symbiotic. Co is the metal component of vitamin B_{12}. Thus, Co deficiency inhibits the formation of leghaemoglobin and, hence, N_2 fixation. The Co content of the shoots can be used as an indicator of Co deficiency in legumes, where the critical levels are between 20 and 40 ppb of shoot dry weight.

BASICS OF PLANT NUTRITION

Plant nutrition is governed by some basic facts and principles concerning nutrient supply, their absorption, transport and production efficiency. These should be understood and applied during practical nutrient management, which is covered in detail in Chapters 6, 7 and 8.

Nutrient demand and supply

Plants require nutrients in balanced amounts depending on their stage of development and yield levels. For optimal nutrition of crops, a sufficient concentration of the individual nutrients should be present in the plant leaves at any time. An optimal nutrient supply requires:

- sufficient available nutrients in the rootzone of the soil;
- rapid transport of nutrients in the soil solution towards the root surface;
- satisfactory root growth to access available nutrients;
- unimpeded nutrient uptake, especially with sufficient oxygen present;
- satisfactory mobility and activity of nutrients within the plant.

The nutrient concentrations required in plants, or rather in the active tissues, are usually indicated on a dry-matter basis, as this is more reliable than on a fresh-matter basis with its varying water content. Leaves usually have higher nutrient concentrations than do roots. These are usually stated as a percentage for macronutrients and in micrograms per gram (parts per million) for micronutrients.

The law of the minimum and its implications

In plant nutrition, there is a law known as Liebig's law of the minimum. It is named after its author, Justus von Liebig, who said that the growth of a plant is limited by the nutrient that is in shortest supply (in relation to plant need). Once its supply is improved, the next limiting nutrient controls plant growth. This concept has been depicted in many ways. One is to imagine a barrel with staves of different heights (Figure 9). Such a barrel can only hold water up to the height of its shortest stave. The barrel can be full only when all its staves are of the same size. A plant can also produce to its full potential when all nutrients (production factors in an enlarged sense) are at an optimal level, i.e. without any deficiencies or excesses.

In order to produce high yields, plant nutrition requires a continuous effort to eliminate minimum factors and provide balanced nutrition in the optimal range (Figure 10). Even if the law of the minimum is only a guiding rule, it serves as a useful basis for nutrient management. In a broader

FIGURE 9
Demonstration of the law of the minimum using a barrel with staves of different heights

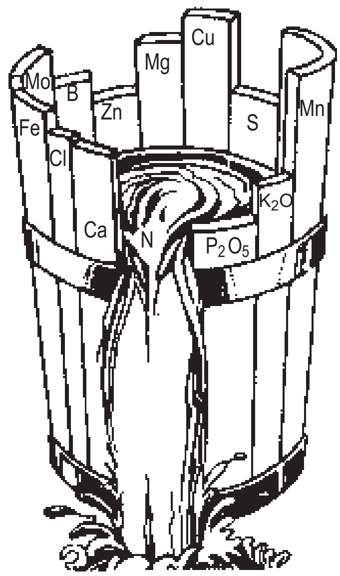
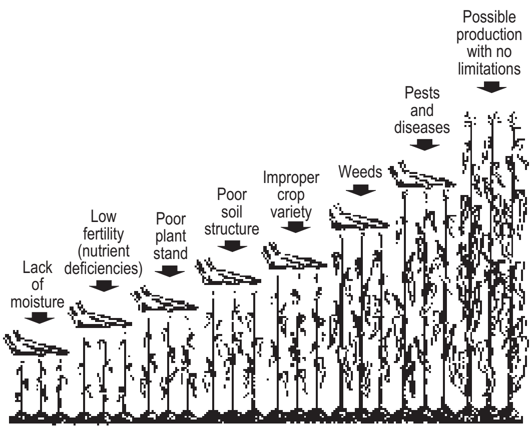


FIGURE 10
Example of yield-limiting minimum factors



sense, the law of the minimum can be extended to include all production inputs, not only nutrients.

Important aspects of the influence of nutrient supply on plant growth are:

- Plants need certain concentrations of nutrient in their tissue for active growth.
- Nutrient requirement comes somewhat in advance of plant growth.
- Insufficient nutrient uptake results in slight to severe deficiencies.
- Slight deficiencies are not visible and denote "hidden hunger".
- Deficiency symptoms indicate a severe shortage of the nutrient in question.
- High yields are only obtained where all nutrients are in the optimal supply range.
- The nutrient with the lowest (minimum) supply determines the yield level.
- Many mistakes in fertilization can be attributed to disregarding the law of the minimum.
- It is easier to correct nutrient deficiencies than to eliminate nutrient toxicities.

Nutrient uptake in time and contents

The pattern of nutrient uptake follows a sigmoid (S-shaped) curve in most cases, being first low in the early stages of crop growth, increasing rapidly when dry-matter production is maximal and then declining towards crop maturity. During vegetative growth, the daily nutrient uptake increases as growth progresses and reaches a maximum during the main growing period.

N, P and K are mainly taken up during active vegetative growth for high photosynthetic activity. The rate of N uptake generally exceeds the rate of dry-matter production in the early stages. Phosphate has an additional small peak requirement for early root growth. Modern high-yielding grain varieties continue to absorb P close to maturity and, like N, 70–80 percent of absorbed P ends up in the panicles or ear heads. For fast-growing crops and high yields, the daily nutrient supply must be adequate, especially during the period of maximum requirement. Field crops generally absorb K faster then they absorb N and P. In rice, 75 percent of the K requirement of the plant may be absorbed up to boot leaf stage. Between tillering and panicle initiation, mean daily absorption rates can approach 2.5 kg

K_2O/ha/day. Unlike N and P, only 20–25 percent of absorbed K is transferred to the grain, the rest remaining in the straw.

During the final stages of growth as the plant approaches its reproductive phase before maturity, nutrient uptake decreases. Perennial plants retrieve most of the nutrients from the leaves before leaf fall and relocate these for future use. In certain plants, such as jute, a considerable proportion of the absorbed nutrients is returned to the soil through leaf shedding before the crop matures.

While the total amount of a nutrient within the plant steadily increases, the concentration (percentage) of the nutrient generally decreases, even with a good supply. The highest concentrations of nutrients are found in leaves at early growth stages, and the lowest in leaves near harvest. This decrease in nutrient concentration over time is because of the transfer to other organs and also what is called the dilution effect, which results from a larger increase in dry matter than in nutrient content. For example, young plants with 50 kg K in 1 500 kg of dry matter contain 3.3 percent K but plants approaching flowering with 100 kg K in 5 000 kg of dry matter contain 2.0 percent K.

The dilution effect makes the interpretation of plant analysis results difficult, but it can be taken into account by relating plant data to a certain stage of growth.

Nutrient mobility and its effect on deficiency symptoms

While nutrients are transported easily from roots to shoots, their redistribution from the original place of deposition is more difficult for the so-called immobile nutrients. In the event of nutrient deficiency, a partial re-activation is required in order to supply newly formed leaves from the reserves of older ones. The relative mobility of a nutrient within the plant is helpful in understanding the reasons for the differential appearance of nutrient deficiency symptoms as discussed above. For example:

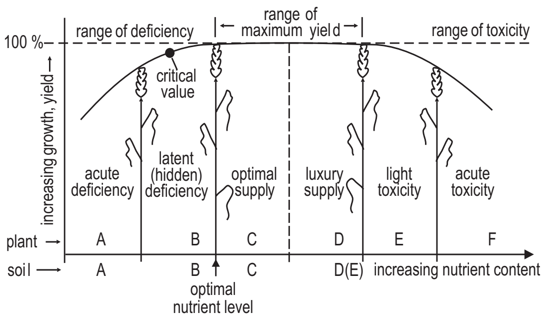
- The appearance of deficiency symptoms on older leaves indicates the shortage of a mobile nutrient because the plant can transport some nutrient quantities from old to new leaves.
- The appearance of deficiency symptoms on younger leaves indicates the shortage of an immobile nutrient because of lack of supply from older to younger leaves.

The range of nutrient supply from deficiency to toxicity

The nutrient status of a plant can range from acute deficiency to acute toxicity. A broad division of nutrient status into three groups namely deficient, optimal and excess may be useful for general purposes. For a more accurate assessment of the nutritional status of plants, detailed categorization is required in which six different ranges can be distinguished (Figure 11):

- Acute deficiency: It is associated with definite visible symptoms and poor growth. The addition of the deficient nutrient usually results in increased

FIGURE 11
Plant growth and yield dependence on nutrient supply



Source: Finck, 1992.

growth and yields. This range should be avoided as its occurrence is a sign of low nutrient supply or poor nutrient management and poor crop performance.

- Marginal or latent deficiency (hidden hunger): It is a small range with or without visible deficiency symptoms. However, growth and yield are reduced. Addition of the yield-limiting nutrient results in higher yields but this may not be visible. Optimal nutrient supply prevents hidden hunger.
- Optimal supply: This is the range to aim for. Here all nutrients are at the most desired level. In this range, healthy green plants, good growth and high yields with good quality can be expected. This range is generally wide for most nutrients. The optimal supply is reached above the critical concentration, which is generally associated with 90 percent of maximum yield. The critical concentration serves as a diagnostic index for nutrient supply through plant analysis (Chapter 4).
- Luxury supply: Although there is no definite borderline between optimal and luxury supply, it is useful to identify this range of unnecessarily high nutrient supply. Even if there may not be any negative effects on plant growth or yield, nutrient input is wasted and product quality as well as disease resistance may be reduced especially in the case of excess N. Therefore, luxury consumption of a nutrient should be avoided. In other words, optimal supply should be maintained and not exceeded except in special cases, such as the need for protein enrichment in grain for quality considerations (Chapter 10).
- Marginal or light (hidden) toxicity: Here the nutrient concentration is moving towards toxicity. Above the critical toxic concentration, crop growth and yield start to decrease because of the harmful effects of a nutrient surplus, or of toxic substances on biochemical processes and imbalances. No symptoms may be evident, as in the case of hidden hunger.
- Acute toxicity: This is the other extreme of excessive supply or poor nutrient management. Plants are damaged by toxic levels resulting in toxicity symptoms, poor or no growth, poor yield, low quality and damage to soil and plant health. The disease resistance of plants may also be lowered and the plant may even die. This range should definitely be avoided for any nutrient.

Nutrient interactions

It is not easy to provide plants with exactly adequate amounts of all nutrients, and the task is made more difficult by numerous interactions between nutrients. On the one hand, nutrients have their individual specific functions as described above. On the other hand, there are also some common functions as well as interactions. These can be positive or negative. Where a nutrient interaction is synergistic (positive), their combined impact on plant production is greater than the sum of their individual effects where used singly. In an antagonistic (negative) interaction, their combined impact on plant production or concentration in tissues is lower than the sum of their individual effects:

- synergistic (positive) interaction:
  - effect of nutrient A on yield = 100,
  - effect of nutrient B on yield = 50,
  - effect of combined use of A and B on yield = greater than 150;
- antagonistic (negative) interaction:
  - effect of nutrient A on yield = 100,
  - effect of nutrient B on yield = 50,
  - effect of combined use of A and B on yield = lower than 150;
- additive effect (no interaction):
  - effect of nutrient A on yield = 100,
  - effect of nutrient B on yield = 50,
  - effect of combined use of A and B on yield = 150.

Where they occur, antagonistic interactions are caused mainly by imbalanced nutrient supply and suboptimal nutrient ratios required for satisfactory growth and development. Therefore, from a practical point of view, many unwanted antagonistic (negative) interactions can be avoided by maintaining a balanced nutrient supply.

The soundness of a nutrient management programme can be judged from the extent to which it is able to harness the benefits that accrue from positive interactions between nutrients and other production inputs. Some available results on the contribution of positive interactions for several pairs of nutrients and other inputs are summarized in Table 7. The synergistic advantage would have been lost and nutrient-use efficiency (NUE) would have been reduced if only one of the two nutrients had been used and the other had been neglected.

Positive interactions have a very high pay-off for farmers, and research must make available all the possible positive interactions for the use of farmers and also tell them how the negative ones can be kept at a safe distance from their fields. The need to harness positive interactions will be felt increasingly

TABLE 7
Some examples of synergistic interactions between nutrients and other inputs

Interacting inputs	Crop	Response attributes to positive interaction (% of total response)
Nitrogen × phosphorus	Wheat	30
Nitrogen × phosphorus	Maize	26
Nitrogen × phosphorus	Sorghum	50
Nitrogen × potassium	Pineapple	46
Nitrogen × potassium	Rice	38
Nitrogen × sulphur	Rapeseed	25
Potassium × boron	Black gram	41
Nitrogen × water	Rice	34
Nitrogen × weed control	Wheat	33
Phosphorus × population	Pigeon pea	26
Phosphorus × weed control	Chickpea	26

Source: Tandon, 2004.

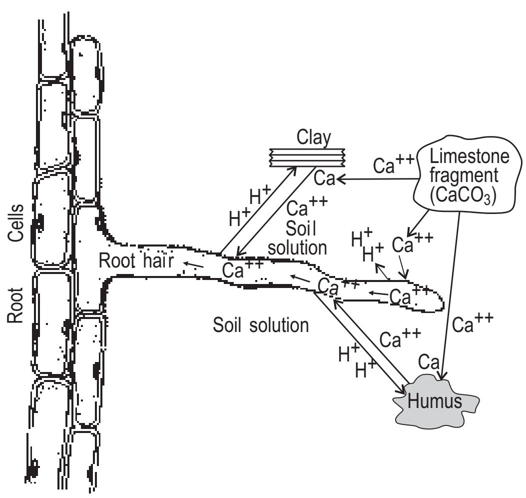
as agriculture becomes more intensive and investments in inputs increase. Cooke (1982) states: “In a highly developed agriculture, large increases in yield potential will mostly come from interaction effects. Farmers must be ready to test all new advances that may raise yield potentials of their crops and be prepared to try combinations of two or more practices.”

ROOT GROWTH AND NUTRIENT UPTAKE

As plants absorb nutrient primarily through their roots, regardless of the type of plant, good growth and proliferation of roots is essential for efficient nutrient uptake. Root growth can be favoured or retarded by soil physical and chemical factors. Even small roots must be able to permeate the rooting volume of the soil in both lateral and vertical directions. The major portion of nutrients is taken up by the root hairs, which are about 1–2 mm long and 0.02 mm wide. These are extensions of the epidermal root cells. Root hairs vastly expand the root surface area.

Many plants develop several million of these hairs with a total length of more than 10 km. Because very close contact with the soil is required, the amount of fine roots is critical and the number and efficiency of the root hairs is also important. Many root hairs last only a few days, but this is sufficient to extract the available nutrients from the adjacent soil volume. As the main roots grow, new root hairs are formed and, thus, there is a continuous exploration of the soil volume to access available nutrients. Anything that affects root growth and its activity affects nutrient uptake.

FIGURE 12
Uptake of nutrients from the soil by a root hair, using Ca as an example



Uptake of nutrients from the soil solution

The available nutrient forms in the soil (Table 6) are free to move in the soil solution by mass flow or diffusion or up and down the soil profile with water movement. Figure 12 illustrates the processes in the vicinity of a root hair. The acquisition of nutrients depends on the size and fineness of the root system, the number of root hairs, the cation exchange capacity (CEC) of the apparent free space (AFS) or the apoplast, etc. A higher CEC results in greater uptake of divalent cations, especially Ca^{2+} (as with legumes). A lower CEC results in greater uptake of monovalent cations such as K^{+}.

The first step in uptake is the entry of the nutrient ion and its passing the outer layer. Nutrients can enter the cell wall without hindrance. Because of their extremely small size (hydrated K ions have a diameter of about 0.001 µm), they are able to penetrate the cell wall tissue of the root hairs. This tissue seems to be a free space and is, therefore, called AFS or the apoplast, a place different from the cytoplast (the real cell substance).

The second step in nutrient uptake involves movement of the nutrient ion into the cytoplast by crossing the membrane. The nutrients must be actively taken up into the interior of the cell. The energy required for this uptake is delivered by root respiration, a process that needs oxygen from the soil air and special uptake mechanisms. Thus, nutrient uptake by roots can be active or passive:

- Nutrients can flow passively through the cell wall (AFS) of the root hairs along with the water.
- The free flow ends at the membrane surrounding the active cell substance (cytoplast).
- Nutrients are actively transported through the membrane by special ion carriers (ionophores).
- Active uptake needs energy from root respiration, which requires sugar and oxygen (O_2).
- Cations are taken up in exchange for H^+ and anions for bicarbonate ions (HCO_3^-) on the root surface.
- Plants can preferentially select nutrients and attempt to exclude unwanted substances.

The fact that nutrient uptake is an active process explains some of its peculiarities. Plants not only accumulate nutrients against a concentration gradient, but they are also able to select from the nutrients at the root surface according to their requirements (preferential uptake). In addition, owing to their selection capacity, they can exclude unwanted or even toxic substances, but this exclusion capacity is limited. After uptake into the cytoplast, the nutrients are transported to the next cells and finally arrive at the xylem, which is the tissue through which water and dissolved minerals move upward from the roots to the stem and leaves. They move to the leaves in these water-transporting vessels where they are used for photosynthesis and other processes.

Nutrient uptake by leaves

Apart from gaseous forms of nutrients (CO_2, SO_2, etc.), leaves are able to take up nutrient ions (Fe^{2+}) or even molecules (urea). Although the outer layer of the leaf cuticle closely protects the plant against water loss, nutrients enter the leaves either via the stomata, which serve for gas exchange, or mainly via small micropores of the cuticle and into the apoplast. Foliar application of nutrients is carried out through dilute solutions in order not to damage the leaf cells by osmotic effects (Chapters 6 and 7).

EFFICIENT USE OF NUTRIENTS

Most nutrient sources added to the soil involve a monetary expense and, thus, should be utilized, as far as possible, during the vegetative growth period in order to obtain a quick return. Some residual effect during the following season should be acceptable, but losses should be kept low. The magnitude and duration of the residual effect depends on the nutrient, soil properties and cropping intensity. Balanced and adequate supply of plant nutrients is important in order to achieve a high degree of nutrient utilization by crops, which also results in lower losses.

In a wider sense, efficient use of nutrients can only be achieved by considering the whole production system. The nutrition of the plant must be integrated into all aspects of crop management. This requires INM in order to become fully effective (Chapter 6).