About this book and its author

This book is published jointly by the International Potash Institute (IPI) and the International Fertilizer Industry Association (IFA). It discusses the possibilities and constraints to food production on the many different soil types found in tropical and subtropical countries. By indicating ways in which crop nutrition and hence crop production can be increased on these soils in developing countries, the author shows ways to ensure food security and improve livelihoods.

Professor Dr. A. Amberger has had much experience in the tropics and subtropics, co-ordinating and organizing agricultural research programmes and serving as a consultant to international organizations. The topics discussed in this book are a synthesis of Professor Amberger's considerable experience and a testimonial to his many years of collaborative scientific effort. The text is based largely on his lectures to students at the Technical University of Munich and at international congresses.

Soil Fertility and Plant Nutrition in the Tropics and Subtropics

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A. Amberger.
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January 2006

Table of Contents

Plates

Acronyms, Symbols and Abbreviations
(as used in this book)

Acronyms

EMBRAPA	Empresa Brasileira de Pesquisa Agropecuaria, Brazil
FAO	Food and Agricultural Organization of the United Nations
FAOSTAT	FAO Statistical Database
ICARDA	International Center for Agricultural Research in the Dry Areas
IFA	International Fertilizer Industry Association
IFDC	International Fertilizer Development Center
IFPRI	International Food Policy Research Institute
IPI	International Potash Institute
IRRI	International Rice Research Institute
ORSTOM	Office de la Recherche Scientifique et Technique d'Outre-Mer, France
PPI/PPIC	Potash and Phosphate Institute / Potash and Phosphate Institute of Canada
SDC	Swiss Agency for Development and Cooperation
UNESCO	United Nations Educational, Scientific and Cultural Organization

Symbols

Al	Aluminium
B	Boron
C	Carbon
Ca	Calcium
$CaCO_3$	Calcium carbonate

$CaSO_4$	Calcium sulphate
Cu	Copper
Fe	Iron
H^+	Proton
HCO_3	Bicarbonate
K	Potassium
KCl	Potassium chloride (=MOP)
KNO_3	Potassium nitrate (=NOP)
K_2O	Potash
K_2SO_4	Potassium sulphate (=SOP)
Mg	Magnesium
Mn	Manganese
Mo	Molybdenum
N	Nitrogen
NH_3	Ammonia
NH_4	Ammonium
NO_2	Nitrite
NO_3	Nitrate
N_2	Dinitrogen
N_2O	Nitrous oxide
NaCl	Sodium chloride
P	Phosphorus
P_2O_5	Phosphate
S	Sulphur
SO_4	Sulphate
Zn	Zinc

Abbreviations

AM	Arbuscular mycorrhizae
AS	Ammonium sulphate
ASN	Ammonium sulphate nitrate
BNF	Biological nitrogen fixation
CAN	Calcium ammonium nitrate
CAM	Crassulacean acid metabolism
CEC	Cation exchange capacity
DCD	Dicyandiamide
DMPP	3,4-dimethylpyrazole phosphate
dS/m	deci Siemens per meter
DTPA	Diethylene triamine pentaacetic acid
EC	Electrical conductivity
EDTA	Ethylene diamine tetraacetic acid
HEDTA	N-(2-hydroxyethyl)ethylenediaminetriaceticacid
PR	Phosphate rock
mM	millimole
MOP	Muriate of potash, potassium chloride
NOP	Nitrate of potash, potassium nitrate
PPD	Phenylphosphodiamidate
SCU	Sulphur-coated urea
SOM	Soil organic matter
SOP	Sulphate of potash, potassium sulphate
SSNM	Site-specific nutrient management
SSP	Single superphosphate
TSP	Triple superphosphate
UAN	Urea ammonium nitrate

1. Introduction

This book considers at both a basic and practical level the constraints to soil fertility and plant nutrition in the tropics and subtropics. It presents strategies for nutrient management for sustainable production that conserve soil resources. It shows ways to avoid errors in agricultural land use that can lead to the deterioration of soils and desertification.

It is dedicated to all those interested in sustainable, environmentally acceptable agriculture including those in research, development and extension work, consultants, progressive farmers, students and decision-makers. The contents are based on literature surveys and personal experience gained over many years especially in Africa, the Near East and Central and South America.

Those who want to work in the tropics and deal with the problems of soil fertility and plant nutrition there must be able to identify the yield-limiting factors in each area. This requires knowledge of the climatic and soil characteristics at their place of work, observation of plant growth and phenological symptoms, and understanding data provided by soil and plant analysis. Only then can strategies be developed and recommendations given that will address local problems.

Meadows *et al.* (1992) voiced the need for a regenerative agriculture, which improves the use of soils and utilises natural processes, and similar needs have been noted in other studies, for example, the IFPRI 2020 Vision (IFPRI, 2002) and World Agriculture Towards 2015-30 (FAO 2002).

The number of undernourished people in the world declined only marginally over the past decade, remaining above 800 million (FAO, 2005). Hunger is prevalent in the tropics and subtropics, areas that are severely affected by soil degradation and loss of soil fertility, and the link between them is obvious. Soil degradation and loss of fertility leads to poor crop yields which, in turn, contribute greatly to food insecurity with subsistence farming that is widespread in the tropics and subtropics.

In summary, the most important goal and challenge in tropical agriculture must be to sustain and, if possible, increase soil fertility and maintain food production for millions of people in an economically, ecologically and socially acceptable way. Knowledge of soil characteristics is a basic requirement for producing location-specific recommendations for maintaining soil fertility. The required increase in soil fertility will not be achieved by organic farming methods alone. Using fertilizers judiciously to supply nutrients for plants is a necessity, and fertilizers in combination with organic manures can maintain and improve soil fertility. This is the only way to satisfy the increasing food demand of an increasing population in the developing countries.

Norman E. Borlaug, Nobel Laureate, noted that:

"To solve the food problem without mineral fertilization is a dream.

The old weathered soils low in pH cannot become productive

without the help of chemical fertilizers".

2. Characteristics of the tropics and subtropics

2.1. Climate and natural vegetation

The tropics are geographically defined as the area between the Tropic of Cancer (23.5°N) and the Tropic of Capricorn (23.5°S), and to both the north and the south of the tropics are subtropical regions. The tropics and subtropics, which together constitute 62% of the earth's surface, are home to half of the world's population. The differentiation of these climatic zones follows temperature and humidity, modified by their position relative to oceans and mountains, and not strictly according to latitude. Instead there is a gradual transition from tropical rain forests near the Equator via semi-humid/semi-arid areas of savannas to arid zones. Climate determines the length of the vegetation period. Tropical crops are short-day (12 hours) and the average temperature in the tropics is more than 18°C throughout the year while in the subtropics this temperature lasts for four months only.

The important crops of the tropics are C_4 plants that are not only much more efficient in photosynthesis compared to C_3 crops, but they also have a much lower transpiration coefficient making them more efficient in water use. Tropical grasses such as maize, sorghum, millet and sugarcane are typical C_4 crops (see for example Marschner, 1995).

Natural vegetation and agricultural land use are closely related to the climate, defined as humid, semi-humid/semi-arid and arid. The amount and distribution of rainfall is an important parameter for tropical agriculture. The amount ranges from zero to several thousand millimeters (mm) per year. In the equatorial zone, it rains every day with no differentiation in seasons. With increasing distance from the Equator, there are rainy and dry seasons during the year. Besides the amount and distribution of rainfall, the relation between rainfall and potential evapotranspiration is important and this varies greatly with climate (Figure 1). For example, in the humid climate of Malaysia, potential precipitation is very large almost throughout the year but is combined with a very small potential evapotranspiration. In contrast, in the arid Sudan, precipitation is very small but potential evapotranspiration is very large. In consequence, according to the climatic zone and soil type, land use and farming systems vary greatly. In all tropical areas, subsistence farming is based on root crops and cereals with only small inputs. In humid areas, after land clearing, more intensive farming is possible, e.g. growing fruits with appropriate agricultural inputs. In semi-arid, rainfed areas, livestock ranching or nomadic herding is dominant. Where irrigation is available multiple cropping is possible, especially with products for export, but greater attention to management is required, especially nutrient inputs.

2.2. Soil formation

Important factors affecting soil formation are climate (temperature, solar radiation and rainfall), mineralogical composition of the parent material, topography and biological activity in the soil. For example, an increase in temperature of 10°C doubles or triples the rate of chemical decomposition of soil minerals and organic matter. As a result, free oxides and hydroxides of iron (Fe) and aluminium (Al) dominate in tropical soils, whereas in moderate climates crystalline silicates are dominant.

Variations in parent material, climatic conditions and land use have resulted in very different soil types. Soil classification, based usually on soil properties, varies between organizations like FAO, USA, UNESCO, EMBRAPA, ORSTOM, and these different systems are not readily compatible. In this book, those soil types found most frequently in the different climatic regions are very roughly classified with respect to possible soil fertility constraints following the FAO system. The classification using the United States system, which emphasizes genetic properties of soils, is given in parenthesis.

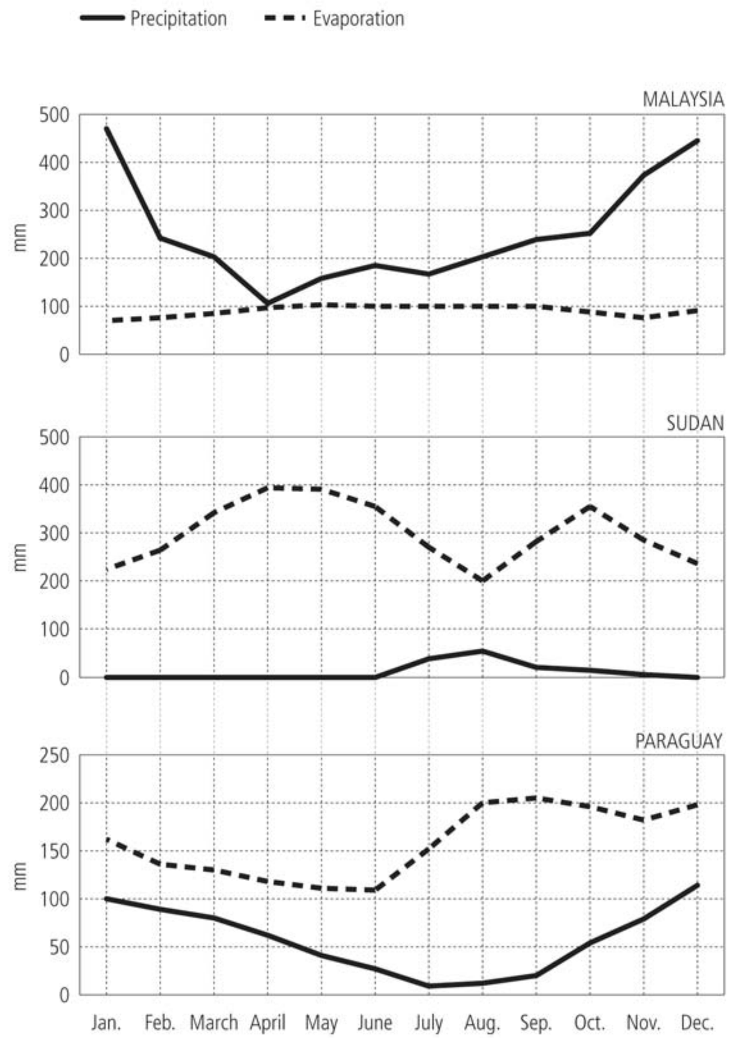

Figure 1. Average precipitation and evaporation in Malaysia (a), Sudan (b) and Paraguay (c). (Adapted from Sanchez, 1976 for (a) and (b) and Amberger, 1988 for (c))

2.3. Factors related to soil fertility

Soil fertility is the result of the interactions between the biological, chemical and physical properties of soil due to soil type and land use, and the effects of climate. It is related to the potential for the sustainable production of crops and animals and can be assessed and/or described in various ways.

2.3.1. Soil colour

Soil colour depends on the type and amount of minerals and organic matter. Black soils are rich in organic matter and often are very fertile, whereas grey soils have little organic matter and poor drainage. Brown soils contain an adequate amount of organic matter, Fe and other minerals, and have good drainage. Red soils have large amounts of oxidized Fe and frequently good drainage but very little organic matter. Yellow soils have both oxidized and reduced Fe with little organic matter and medium drainage.

2.3.2. Soil physical properties

Soil physical properties include structure, texture, consistency, porosity and water holding capacity. The structure of a soil is related to the arrangement of mineral particles into aggregates, which influence the air and water content of the soil, its ability to retain water and its drainage characteristics.

Soil texture is concerned with the size of the mineral particles, which determines the surface area of the soil. At a simple level, according to particle size, there is clay (<0.002 mm), silt (0.002-0.05 mm), sand (0.05-2 mm), and stones (>2 mm). Soils with a large content of clay become hard when dry and sticky when wet.

Soil consistency is related to the compression/compaction and plasticity of a soil and influences tillage and other mechanical operations. Soil organic matter has an effect on consistency by helping to bind mineral particles together. The sensitivity of a soil to erosion is related to texture and consistency.

Soil porosity refers to the total volume of pores in the soil. Pores can be filled either with air or water. Large pores allow the rapid exchange of air and drainage of excess water. Small pores retain water against drainage and the availability of this water for crops depends on the diameter of the pores. Clay soils are characterized by having many small pores with a large water holding capacity, but not all of this water is available to plants.

2.3.3. Soil chemical properties

Soil chemical properties are related to the supply of plant nutrients that are essential for plant growth. Chemical elements are released from clay minerals and organic matter into the soil solution from where they can be absorbed by plant roots or microorganisms. Nutrient adsorption and release are important properties of soils related to the amount of soil organic matter (SOM) and the amount and type of clay minerals and their ability to hold and exchange cations or anions. The cation exchange capacity (CEC) is an important factor in soil fertility. The availability of nutrients to plants depends on soil pH (soil acidity) and the redox-potential. The total salt content measured as electrical conductivity (EC) of soil is of great importance in irrigated agriculture.

Phosphorus (P) is an essential, irreplaceable element for all living organisms and crop production depends on there being an adequate supply (Table 1) (see also Johnston, 2000). Crops do not respond to nitrogen (N) when P is deficient. Deficiency of plant-available P can be due to two factors. The first is where P is chemically bound as Fe or Al phosphate, as in sandy acid Ferralsols. The second is the capacity of Fe and Al oxides and some clay minerals to strongly adsorb P added in water-soluble forms, as in loamy Nitosols. This latter process is reversible. The extent of P fixation can be estimated analytically by determining the buffer curve of a soil (Langmuir adsorption isotherms).

Strong P adsorption is minimized when other anions compete with phosphate ions on the sorption sites of Fe and Al oxides and clay minerals, thus

Table 1. Root and shoot growth of two strains of bean grown with adequate and inadequate amounts of phosphorus (Adapted from Marschner, 1986)

Strain number	Adequate P-supply Dry wt (mg/plant) Root	Shoot	Root/shoot ratio	Inadequate P-supply Dry wt (mg/plant) Root	Shoot	Root/shoot ratio
6	242	1,465	0.17	124	777	0.16
11	181	1,265	0.15	365	1,141	0.31

making P more available. Such anions include hydroxyl (OH^-) and bicarbonate (HCO_3^-) ions, e.g. following lime applications, and also soluble silicates and organic anions from soil organic matter. Therefore, under the conditions of the humid tropics, P fertilizers that also contain silicates (e.g. basic slag and thermal phosphates) have proved to be superior to water-soluble phosphates (e.g. triple superphosphate, TSP). This is because silicate ions are adsorbed on sites able to adsorb phosphate ions.

Figure 2 shows some other possibilities for the mobilization of soil-borne P. In the process of nutrient uptake, plant roots release protons (H^+) that create a pH in the rhizosphere sufficient to solubilize many water-insoluble P compounds. Some crops are more efficient at this than others, e.g. chickpea, white mustard, white lupin, rape and buck wheat, so called P-efficient plant species, compared to wheat, sorghum and maize (Plate 1). Such P-efficient plants are better able to utilize small amounts of P in soil. For example, in the presence of an inadequate soil P supply, bean strain 11 in Table 1 had nearly double the amount of root and double the root/shoot ratio (dry weight basis) compared to bean strain number 6.

Plant roots also release chelating and reducing substances, such as organic acids, amino acids and phenols. Chelates can solubilize Fe and Al phosphates by producing stable Al and Fe chelates (Figure 2a), and solubilize apatite phosphates by chelating calcium (Ca) ions (Figure 2c) (Amberger, 1992). The release of chelating and reducing substances is widespread among woody plant species that form root clusters. Microorganisms also act in the same way, producing H^+ and different chelating organic acids when decomposing organic matter (Figure 2d). For example, application of “Hyperphos” (a phosphate rock (PR) from Tunisia) gave similar yields of clover as did basic slag or superphosphate by decreasing soil pH in the rhizosphere from 6.2 to 4.6. Mycorrhizal associations with roots of crop plants also are helpful in making P plant available in calcareous soils by releasing oxalic acid (Table 2).

Developing P-efficient cultivars would be a more economic approach to cropping that is favourable to small-scale farmers who have to manage their crop production with no, or only small inputs. This benefit, however, has a downside effect because cropping without P inputs will deplete soil P reserves more quickly. But if some part of the extra income generated by the increased yields is used to buy P fertilizer then there should be no problem.

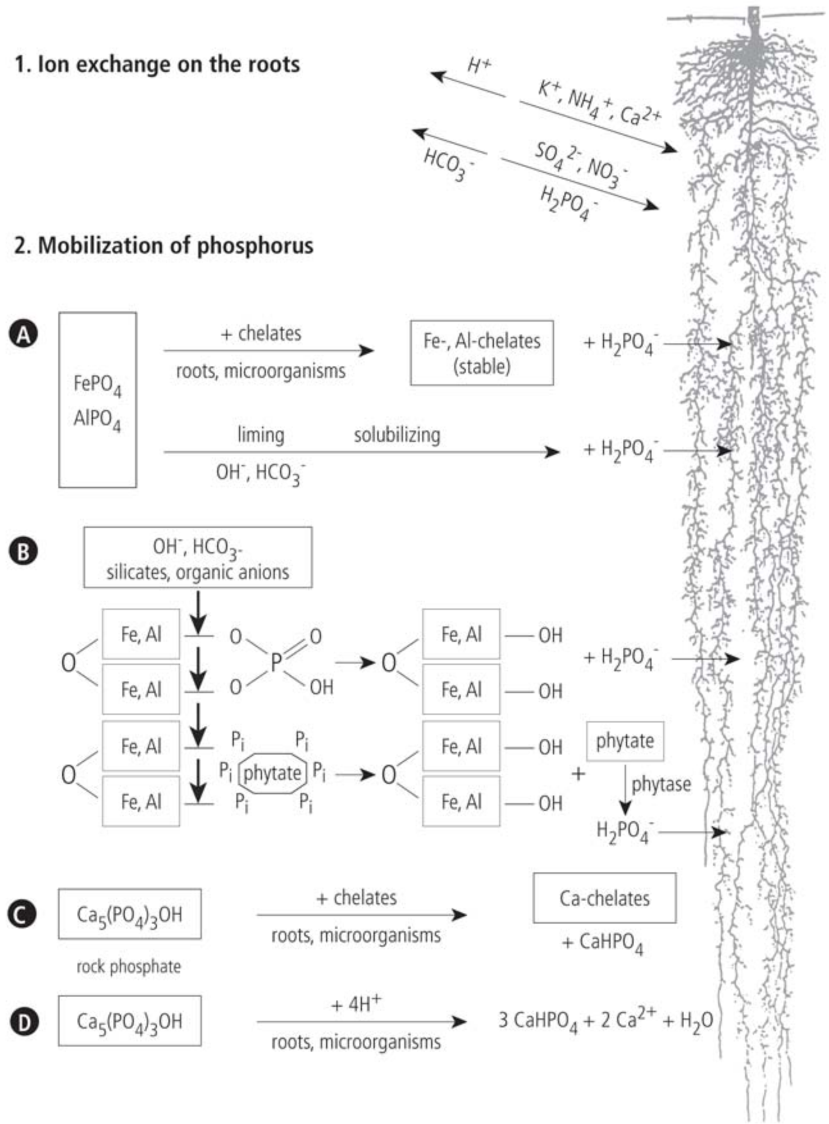

Figure 2. Schematic representation of phosphorus mobilization in soil and uptake by roots

Table 2. Dry weight of wheat roots and shoots and total P in shoots when plants were grown with (+) and without (-) arbuscular mycorrhizal (AM) fungi (Adapted from Li *et al.*, 2001)

Treatment	Dry weight (g/pot)		Total P in shoots (mg/pot)
	Shoots	Roots	
– AM	4.0 ± 0.6	0.9 ± 0.4	4.2 ± 1.2
+ AM	7.1 ± 0.1	1.3 ± 0.1	6.1 ± 0.2

Base cations such as potassium (K), Ca and magnesium (Mg) become deficient in the acid soils of the humid tropics. This is due to the small amount in the parent material, the small CEC to retain them against leaching and their removal by erosion. Very large losses of K can occur after forest has been cut and removed (Likens *et al.*, 1994). Losses through soil erosion greatly exceed those by leaching, highlighting the need to minimize erosion. Burning the above ground vegetation as a part of shifting cultivation, only leads to a short transitory increase in the amount of base cations from the ashes. Growing cash crops, such as vegetables, fruit trees, oil palm, coffee, coconut and tuber plants that have a large requirement for these nutrients quickly results in deficiencies or imbalances. In cases of severe deficiency, soluble compounds of K, Ca and Mg can be applied as foliar sprays and crops will show a rapid response.

Potassium has an irreplaceable role in a number of functions in plants but only small amounts are required relative to the much larger quantities needed to fulfil its role as an osmotic regulator in all cells (Johnston *et al.*, 2001). Plants well supplied with K are more resistant to pests and diseases. Furthermore, beneficial effects of K on the chilling tolerance of plants grown in a warm climate and to photooxidative stress under high light intensity are well documented (IPI, 2003, and references therein).

Calcium is important in cell membrane stabilization and enzyme modulation. Consequently, Ca deficiency exhibits itself as the disintegration and collapse of cell walls, mainly seen in vegetables and fruit trees, which have a large Ca requirement.

Magnesium is involved in many metabolic processes. Chlorotic or necrotic spots spread over the leaves indicate deficiency. Regular applications of calcitic or dolomitic amendments are required to prevent deficiency.

Sulphur (S) deficiency is becoming more frequent due to leaching and to sorption of sulphate ions (SO_4^{2-}) on sesquioxides in the soil, particularly in Ferralsols, but also due to desorption as a consequence of increased applications of P fertilizers. The only soil-borne source of S is organic matter after microbial decomposition and mineralization. Oil palm, vegetables, fruit trees and legumes have a particularly large requirement for S. To meet this requirement, S can be applied as ammonium sulphate (AS), ammonium sulphate nitrate (ASN), single superphosphate (SSP), potassium sulphate (SOP), gypsum ($CaSO_4$) and elemental sulphur. Sulphur-coated urea (SCU) is not only a source of S, but also the S delays the transformation of urea, which may reduce leaching of nitrate (NO_3).

Micronutrients can be very important in tropical agriculture because they can be deficient in many soils. Deficiency is due to losses by leaching from the highly weathered soils. The topic is discussed in more detail in Chapter 8.

Liming by increasing soil pH, drastically decreases Al and manganese (Mn) toxicity. It also increases the availability of P by both solubilizing Fe and Al phosphates and desorbing phosphate ions from sesquioxides. Tropical soils are particularly sensitive to overliming, and adding small amounts of lime are usually sufficient to produce good yields. Liming should be done frequently because Ca and Mg ions are not readily retained in many tropical and subtropical soils due to their low buffering capacity. Using dolomitic material supplies both Ca and Mg. Maize and legumes show a good response to liming.

2.3.4. Biological properties

In a fertile soil there is a large number of living organisms (microflora and microfauna), which vary greatly in size and function. One group is responsible for the decomposition of added and existing organic matter. This process brings plant nutrients in the organic material into inorganic forms that are available for uptake by plant roots. Some bacteria capable of fixing atmospheric N exist in nodules on the roots of legumes (biological nitrogen fixation, BNF); others are free living in the rhizosphere.

Mycorrhizal fungi play an important role in nutrient acquisition in many plant species. A mycorrhiza is a close symbiotic association of a fungus and a root of a higher plant. Two types of association are important for plant nutrition. The arbuscular mycorrhizae (AM) can invade a root developing an internal mycelium, together with a considerable length of external mycelium that greatly increases the effective length of the root. The ecto-mycorrhizal fungi typically form a dense sheath of hyphae around the root with a web of hyphae between the cortical cells (Tinker, 1980). Most important are the AM that are found in almost all tropical and subtropical crops. All mycorrhizae take carbon compounds fixed by photosynthesis in the leaves from the host plant and, in return, supply it with nutrients, particularly P and micronutrients, which they take up from the soil solution. This symbiosis is of great importance in soils poor in P and micronutrients, especially zinc (Zn). There are differences between AM genotypes, e.g. between those utilizing Al phosphates in acid soils and those using hydroxylapatites in neutral/alkaline soils. Mulching with plant residues favours the development of mycorrhizal fungi. The efficiency of AM is constrained by low temperature, water stress and soil $pH<5.0$ as well as by salinity, toxic concentrations of Al, Fe and Mn, and also by large additions of soluble P fertilizers.

2.3.5. Soil fertility and early approaches to the use of fertilizers in developed and developing countries

In Europe, agricultural systems using inputs of added nutrients have developed slowly since the mid-1800s. Such systems now rely on inputs of plant nutrients from fertilizers to supplement the supply from the soil and nutrients returned in organic materials. A number of steps can be identified in the use of fertilizers in European agriculture. First, widespread P deficiency in soils had to be corrected and this was made possible by the industrial scale production of superphosphate in the mid-1800s. At that time, limited amounts of N were available as ammonium sulphate (a by-product of town gas production) and sodium nitrate from the natural deposits in Chile. By the mid-1850s, wood ash was the main source of K, the large deposits of K-bearing salts in Germany were not discovered until the 1860s. Emigrants from Europe to North America took European methods of agriculture with them. These included crop rotations, which optimized the use of indigenous plant nutrients in soil. It was not until the early years of the 20th century that the industrial fixation of atmospheric N was achieved (ammonia synthesis by Haber/Bosch; urea synthesis by Wöhler). Even then, however, large amounts of N were not used in agriculture because the available crop cultivars did not have the yield potential to respond to large applications. It was not until after the 1950s that fertilizer N use increased greatly, a time that also saw a large increase in the use of P and K fertilizers. Today, agricultural productivity in many developed countries relies heavily on the input of nutrients from fertilizers. The financial returns allow these and other inputs to be purchased by farmers.

In developing countries, rapid improvements in agricultural productivity, especially after the 1950s, were required to achieve food security for an increasing population. There was little information on the existing fertility of many soils. Following the trends that were evolving at that time in developed countries, there was a considerable increase in N fertilizer use that was not matched by an appropriate increase in the application of P and K fertilizers. This has led to soil nutrient mining, especially of K, in many parts of the developing world. The present situation is exacerbated by the fact that many small farmers in developing countries lack adequate resources to purchase manufactured fertilizers, especially P and K fertilizers. In consequence, they have sought to use locally available PRs to supply P. Fertilizer use is discussed in more detail in Chapter 2.5.

2.4. Constraints to crop production

2.4.1. Soil erosion

Erosion is a major problem in many countries in the tropics and subtropics (Plate 2). Erosion, defined as lateral transport of soil particles by water and wind, depends on many factors. These include the amount, duration and intensity of rainfall (erosivity), the impact energy of the raindrops, surface vegetation cover, the size of the soil particles (erodibility), topography and degree of slope and exposure. A large content of silt and fine sand in soil promotes erosion. The loss of eroded topsoil with its organic matter and nutrients, and the resulting decrease in depth of soil that can be explored by roots, causes a considerable loss of soil fertility. Eroded soils have little structural stability and are prone to develop physical problems like crusting, compaction and pan formation. Luvisols are especially vulnerable to these problems. Large scale mechanized farming with inappropriate soil cultivation can cause losses of soil of 100 t/ha and more per year, and the use of heavy machinery can cause serious compaction.

In areas of permanent natural grassland there is normally no erosion, and erosion is negligible where there is a permanent crop canopy. However, the danger of erosion by water and wind increases rapidly with arable farming (Table 3). Where natural vegetation is cleared by "slash and burn" as a preparation for growing crops, erosion can become a serious problem. In semi-arid areas, soil aggregates of poor stability are transported by wind and severely

Table 3. Amount (t/ha) of soil lost annually by erosion under three cropping systems at four locations in West Africa (Adapted from Sanchez, 1976)

Locality	Forest land	Cultivated land	Bare soil
Ouagadougou, Burkina Faso	0.1	0.6 - 8.0	10 - 20
Sefa, Senegal	0.2	7.3	21
Bouaké, Senegal	0.1	0.1 - 26	18 - 30
Abidjan, Côte d'Ivoire	0.03	0.1 - 90	108 - 170

damage plants physically in the early stages of growth. Furthermore, wind erosion removes the smaller soil aggregates leading to a reduction in the water holding capacity.

There are various methods to prevent or minimize erosion. One example is community management for the harvesting of rainwater, its conservation and economic use. Others, where crops are to be grown, are the formation of terraces, preparing soil and planting along contours, using minimum or zero tillage and surface mulching (Table 4). Erosion can also be controlled efficiently and sand dunes stabilized by building small stone walls and fences. Also hedges of locally-adapted fast growing trees such as *Eucalyptus, Populus, Sambucus, Casuarina*, etc., or shrubs and strips of grasses, such as *Andropogon gayanus* (a perennial grass), *Vetiveria* (a very hard and resistant grass) or Elephant grass can be established.

Table 4. Percent of rainfall that appeared as runoff under maize, with and without mulch, and forest on land with different slopes (Adapted from Bornemiza and Alvarado, 1975)

Slope (%)	Under maize		Forest cover
	Unmulched	Mulched	
1	6.4	2.0	1.7
5	40.3	7.7	1.3
10	42.7	5.7	1.7

Good soil management practices should encourage minimum tillage, leaving crop residues on the soil surface, and direct seeding. Surface mulching conserves soil moisture, enhances water infiltration and increases nutrient availability. Using crop rotations that maintain a vegetative cover on the soil surface minimizes erosion. Alley cropping, a part of agro-forestry, also offers advantages through alternating strips of agricultural crops and hedges of shrubby legumes. Balanced fertilization leading to larger crops and crop residue returns to the soil, together with specific soil conservation techniques, greatly help prevent losses of surface soil through erosion.

Erosion is symptomatic of inappropriate soil management and results in the deterioration and breakdown of soil structure and fertility of fragile tropical soils. Reclamation of such soils is very costly and sometimes not possible.

2.4.2. Drought

A large negative water potential in a soil limits the uptake of water and nutrients by roots. Proper soil cultivation can help to reduce the impact of drought. Minimum tillage and moderate soil preparation decrease evaporation. Covering the soil surface with a mulch of crop residues benefits the water holding capacity of a soil and rainwater conservation. Seeding just before rainfall is expected is a further valuable measure against the adverse effects of drought.

In climatic conditions where there are frequent drought periods and on soils with little water holding capacity, e.g. Rendzinas, K plays an important role in counteracting water stress. Plants well supplied with K (>1% K in dry matter) have a low transpiration coefficient (g water transpired per g dry matter produced) and economize in water use by optimizing stomata regulation and thus reducing transpiration.

Over a long period, ICARDA has screened for drought-tolerant cultivars and developed appropriate crop management techniques for drought conditions using deep-rooting and drought-tolerant crops or varieties. Barley is more tolerant of drought than wheat. There is considerable genetic potential among cereals, grasses and legumes that could be exploited to combat moisture stress. C_4 plants (tropical grasses) and CAM-plants (*Crassulaceae*) are known for very efficient water utilization and low transpiration.

2.4.3. Toxicity

Aluminium toxicity occurs in acid soils. A concentration of exchangeable Al ions greater than 1 ppm in the soil solution leads to Al toxicity, and Al saturation of the CEC can be 70% and more (Figure 3). Such large concentrations of Al restrict the development of roots, which become brown, thick, short and stunted, and this effects both water and nutrient absorption, as well as the nodulation of legumes. Aluminium toxicity can also be associated with Mn toxicity seen as chlorotic speckling on leaves and impaired nodulation in legumes, due to a large concentration of Mn ions in poorly drained soils. Crops sensitive to excess Al include sugarcane, soybean, maize and tobacco.

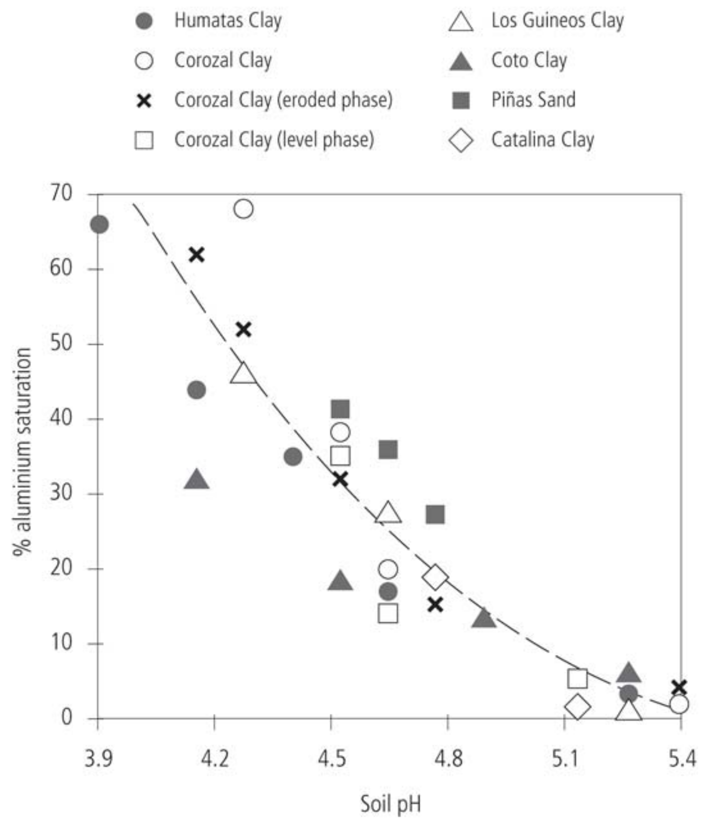

Figure 3. Relationship between soil pH and percent aluminium saturation of the cation exchange complex in eight Puerto Rican soils (Adapted from Bornemiza and Alvarado, 1975)

There are great genetic differences between crops and cultivars in their tolerance to Al and Mn toxicity and soil acidity (Figure 4). Aluminium-resistant plants like tea or Al-tolerant plants such as cassava can withstand up to 40% Al saturation. They do this by releasing large amounts of chelating ions such as citrate, oxalate and malate, and phenolics or flavonoids that form stable complexes or non- or less-toxic compounds with Al ions. The chelating substances released by Al-tolerant plants and microorganisms also desorb fixed phosphates in exchange for organic anions and also help to mobilize insoluble Fe and Al phosphates. They do this by forming strong complexes with Fe and Al and thus releasing P that is then available for uptake by roots and microorganisms. The roots of these varieties are also associated with mycorrhizal fungi that increase the uptake of P by roots. Identifying and making available cultivars with this detoxifying Al exclusion mechanism would be of great help to small-scale farmers who often cannot afford the large transportation costs for lime and fertilizers, even if they are available locally.

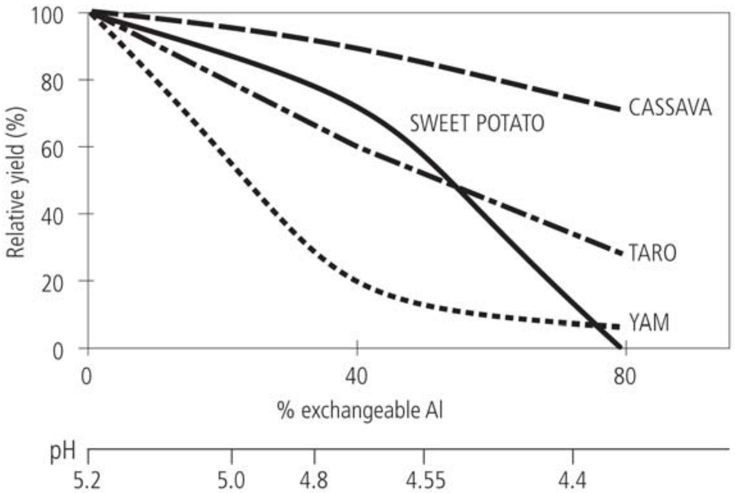

Figure 4. Relative yield of some tropical root crops related to soil pH and exchangeable aluminium (Adapted from Marschner, 1986)

2.4.4. Salinity

Salinity is a particular problem in many areas where there is insufficient rainfall. It is discussed in more detail in Chapter 7.

2.4.5. Soil nutrient mining and soil fertility

Many soils in the tropics and subtropics are highly leached and have only small amounts of plant nutrients. Subsistence farming, which is widespread, leaves little opportunity for farmers to afford fertilizers to replace the nutrients removed from their soils in harvested crops. Equally where slash and burn is practised as a method of food production, population pressure ensures that fallow periods are not long enough to restore soil fertility. Additionally, animal grazing on plant residues after harvest is a common practice that also removes plant nutrients. In all cases, the over-exploitation of natural resources through the permanent depletion of soil-borne nutrients leads to ever declining yields and eventually desertification of the soil. It is important that policy makers are aware of the dangers of soil nutrient mining and its likely effect on national food security. An important role for farm advisors is getting the message to farmers that soil nutrient mining leads to loss of soil fertility, yield potential and falling income. Farmers must be told how to make nutrient balances (nutrient applied *minus* nutrient removed in the harvested crop) for their fields and farms using knowledge of the yield and the likely nutrient content taken from tables of data (see for example Table 5). More detailed information on the nutrient requirement and uptake by many crops is given in Halliday *et al.* (1992) and FAO/IFA/IFDC (2003).

Mismanagement affects both grazing and arable farming. Attempts to increase productivity without adding nutrients to a soil already almost degraded to the point of desertification, will definitely fail. Many light textured soils in Africa and the Near East are to varying degrees becoming depleted of P, K, Mg and micronutrients due to leaching, erosion and nutrient offtakes in harvested crops. To correct such depletion, annual applications of both fertilizers and organic manures are needed. The most appropriate choice will depend on soil type. For example, untreated PR of sufficient reactivity can be as good a source of P as is processed phosphate fertilizer when used on acid soils. Such PRs have been shown to be very effective in the reclamation of many P deficient, acid upland soils (Johnston and Syers, 1998 and papers therein). However, there is no comparable source of K. Potassium chloride and

Table 5. Estimates of total nutrient uptake per tonne economic yield for crops grown under semi-arid conditions (Adapted from IFDC, 1988)

Crop	N	P_2O_5	K_2O (kg)	Ca	Mg	S	Zn	Fe	Mn (g)	Cu	B	Mo
Rice	20	11	30	7.0	3.0	3.0	40	153	675	18	15	2
Maize	26	14	36	5.4	7.8	3.8	130	1,200	320	130	-	-
Wheat	25	9	33	5.3	4.7	4.7	56	624	70	24	48	2
Sorghum	22	13	34	6.4	4.8	2.8	72	720	54	6	54	2
Pearl millet	42	23	91	-	-	-	40	170	20	8	-	-
Chickpea	46	8	50	-	-	-	38	58	30	14	-	-
Pigeon pea	64	18	42	-	4.0	3.3	24	40	14	14	-	-
Groundnut	58	20	30	28.0	7.3	5.7	28	1,500	118	15	133	4

potassium sulphate both contain water soluble K, which is retained in soils in both exchangeable (and readily plant-available) and non-exchangeable (less readily available) forms. On soils with little CEC and depending on the soil minerals, K may migrate to sites within the crystal lattice where it is no longer available to plants, at least in the short term, or be lost in drainage water. To saturate the sites holding non-exchangeable K, large amounts of K are often required. Cereals and legumes grown by small-scale farmers need moderate amounts of K. High-yielding crops such as cotton, maize, soybean, sorghum or intensively managed grass pastures (e.g. Elephant grass or Pangola grass) require large amounts of K, which should be applied after each harvest or for each grazing period. The amounts applied should be based on the expected removal in the harvested crop, which will be related to the expected yield. At present, in Africa and the Near East, the application of K is increasing slowly but there are many cases where the amounts applied are less than those removed in the harvested produce. The important role of K in Asia has been discussed in detail (IPI, 1995).

Food security in the West Asia and North Africa (WANA) region is threatened by the negative K balance in many farming systems (IPI, 1997). The mining of soil K reserves in this region is apparently due to an incorrect interpretation of the K status of the different soils and neglecting the continuous export of K (Krauss, 1993). Alluvial soils apparently contain little

available K due to the rapid transfer of added K to non-exchangeable forms. This occurs more with smectite (Figure 5) than with vermiculite minerals, while illite is a fairly good source of plant available K. Furthermore, the increasing application of N and P fertilizers without K leads to nutrient imbalances. In West Africa, the N: K ratio in applied nutrients is about 1: 0.08, vastly different to the N: K ratio taken up by plants. Citrus on the alluvial soils of Egypt responded to applications of K with a 4-26% increase in yields. In contrast, in Israel fertilizer use is well balanced with an average ratio of N: P: K of 1: 0.4: 0.6. Also, in Morocco, the K balance is negative regardless to the cropping system. Stagnant and decreasing yields due to incipient K deficiency are not surprising. Potassium deficiency symptoms are often seen on vegetables and on fruit trees used to produce food for local consumption. Potassium deficiency can be much more serious for marketable crops, such as oil palm, cotton and potato that have a large demand for K. Much data confirm the need for K for large yields of high quality produce. Potassium should preferably be applied to non-cereal crops in the rotation on account of the better ability of grass species, with their extensive root systems, to acquire K from the soil.

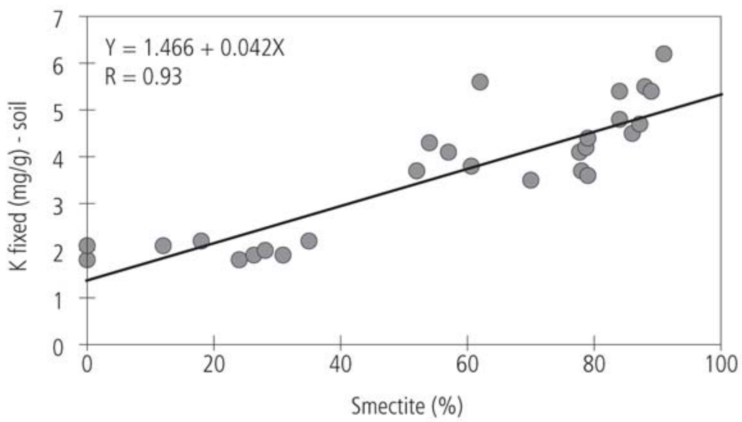

Figure 5. Relationship between percent smectite in soil and potassium fixation in wet Chaouia and Gharb soils (19.92 mg K were added per g clay) (Adapted from Badraoui and Agbani, 1992)

The maintenance of the P and K status of soils depends on the return of crop residues and P and K fertilization. Negative balances due to the continuous mining of the soil's P and K reserves are expensive to correct. Magnesium can be replaced through adding dolomitic material and, when urgent, through foliar applications of magnesium sulphate. Always, the goal must be to maintain and, if possible, increase soil fertility.

2.5. Nutrient sources

2.5.1. Nitrogen fertilizers

Urea and AS are widely used in the tropics and are best applied in bands or placed or given as split applications. Urea is also applied as a foliar spray. Calcium nitrate is not widely used commercially because it is deliquescent. However, it has been used in experiments to supply nitrate (NO_3) for comparison with ammonium (NH_4) fertilizers.

Decomposition of urea ($CO(NH_2)_2$) to NH_4 through the ubiquitously present enzyme urease is temperature dependent and takes about a week. Transformation from NH_4 to nitrite (NO_2) by *Nitrosomonas* bacteria, depends on soil pH and temperature, whereas the further oxidation of NO_2 to NO_3 by the bacteria *Nitrobacter* and *Nitrosolobus* is rapid.

$CO(NH_2)_2 + H_2O$	<u>urease</u>	$2NH_3 + CO_2$
$2NH_4^+ + 3O_2$	<u>*Nitrosomonas*</u>	$2NO_2^- + 2H_2O + 4H^+$
$2NO_2^- + O_2$	<u>*Nitrobacter*</u>	$2NO_3^-$

When urea and urea-ammonium-nitrate (UAN) solutions are applied to bare soil, there is a risk of large losses of ammonia (NH_3) by volatilization. To minimize such losses, such fertilizers should be immediately incorporated into at least the top few centimetres of soil. The efficiency with which urea is used in the tropics can be improved by addition of a urease inhibitor, such as N-(n-butyl)thiophosphoric triamide (NBTPT) or phenylphosphodiamidate (PPD), which inhibits the activity of urease for about two weeks. In an experiment with ^{15}N-labelled urea, the loss of NH_3 from the soil was less with urea plus PPD than from calcium ammonium nitrate (CAN), but the largest loss was from urea alone (Table 6). Such inhibitors have gained practical and commercial importance.

Table 6. Percent nitrogen lost as ammonia from different nitrogen sources (Adapted from Mokwunye and Vlek, 1986)

Fertilizer source	^{15}N loss from soil as ammonia (% after 4 weeks)
Urea (broadcast)	18.4
Urea + PPD (broadcast)	1.9
CAN (broadcast)	7.1

The efficiency of urea and NH_4-containing N fertilizers such as AS and ASN can also be improved through the addition of a nitrification inhibitor such as dicyandiamide (DCD), DCD/1,2,4-Triazol (a mixed stabilizer) or 3,4-dimethylpyrazole-phosphate (DMPP). Zerulla *et al.* (2001) discussed the use of DMPP in detail. When such inhibitors are incorporated in NH_4-containing fertilizers such as AS and ASN or urea, the efficiency of N use is improved (Table 7). The rates used vary according to the specific activity of the inhibitor. Ammonium nitrate or urea applied in site-specific optimum amounts and amended with DMPP at about 1% relative to the content of NH_4-N or urea-N increased yields substantially.

Table 7. Effect of adding a nitrification inhibitor (DMPP) to two nitrogen fertilizers (urea and ammonium sulphate nitrate, ASN) on the yields of wheat, rice and maize (Adapted from Pasda *et al.*, 2001)

Crop	N fertilizer	N rate (kg/ha)	Yield (t/ha)
Winter wheat	without N	-	4.47
	ASN	180	7.96
	ASN + DMPP	180	8.21
Wetland rice	without N	-	5.47
	urea	120	7.20
	urea + DMPP	120	7.49
Grain maize	without N	-	6.69
	ASN	140	9.10
	ASN + DMPP	140	9.34

The effect of DCD and DMPP on *Nitrosomonas* is bacteriostatic, only temporarily inhibiting its activity because these inhibitors are decomposed abiotically and biotically (Wissemeier *et al.*, 2001). In an incubation experiment, urea was added to a sandy Cambisol (Inceptisol) with $pH_{(KCl)}$ 4.8 at a rate corresponding to 130-200 kg N/ha. In this strongly acid soil from Costa Rica, the transformation of NH_4 to NO_3 was completed after four weeks with only a small effect of temperature. Adding DCD, at a rate equivalent to 10% of the total fertilizer N, significantly decreased the transformation of NH_4 to NO_3 and after five weeks the greater part of the applied N was still present as NH_4 (Figure 6).

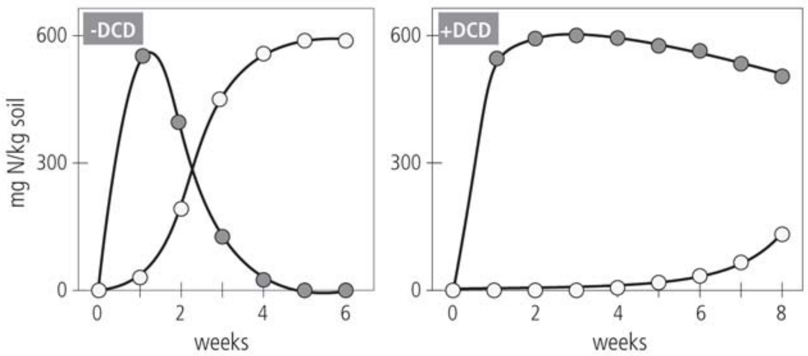

Figure 6. Decomposition of urea to NH_4 (—●—) and NO_3 (—○—) at 20°C with and without adding dicyandiamide (DCD) (Adapted from Vilsmeier *et al.*, 1987)

Decreasing N losses through volatilization when urea is applied with a urease inhibitor, or by leaching and denitrification when N fertilizer is amended with a nitrification inhibitor, has great potential to improve N use efficiency. The implication is that the same yield could be obtained with less N, or a larger yield with the same amount of N. Thus, the use of nitrification and urease inhibitors could benefit farmers and reduce losses to the environment (Trenkel, 1997).

Ammonia volatilization and denitrification losses are especially likely on heavy-textured, clayed Vertisols. Split applications and the immediate incorporation of applied urea into a few centimeters of soil are strongly recommended. This applies particularly for soils without a vegetative cover and

where the CEC, which binds NH_4, is small. In addition, the pH rise during urea hydrolysis may promote NH_3 volatilization losses.

When urea is broadcast without immediate incorporation, N losses of up to 50% and more can be expected. CAN is significantly less liable to losses of such magnitude (Figure 7). When properly applied and incorporated immediately, both banded urea and broadcast CAN give more or less equal yields in subhumid climates. Although not widely used in the tropics and subtropics, CAN is often used in experiments as a source of NO_3 that is immediately available for crop uptake. It is also a suitable source of N for fertigation. On very light textured soils in semi-arid climates, CAN can significantly outperform urea on grain crops, such as sorghum, millet and maize.

Using the most appropriate N fertilizer at the correct time is essential. The total amount of N required by a crop depends on the expected yield, which is related to climate and soil type. From this value can be subtracted the N from legumes and the mineralization of soil organic matter (SOM) and added plant residues. The difference will be the amount of mineral fertilizer N to apply. The total amount of N required can be divided between a number of applications. The soil N supply can be estimated in field trials using control plots to which no N is applied. Of the applied fertilizer N, on average, a crop takes up only about 45% and usually less in semi-arid zones. The rest is lost by volatilization as NH_3, denitrification or leaching as NO_3, or it can be retained in the soil.

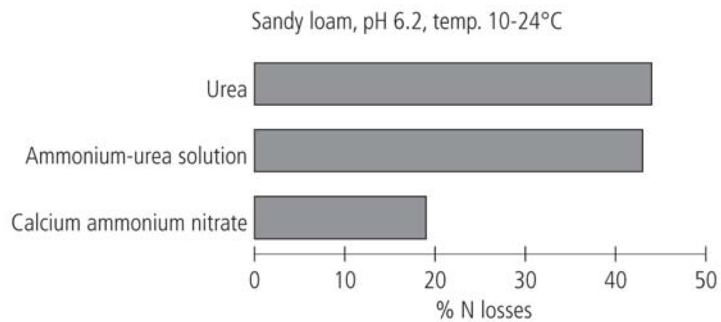

Figure 7. Percent nitrogen losses after broadcasting three different types of nitrogen fertilizer each added to supply 150 kg N/ha (Adapted from Amberger, 1990)

Over-supply or incorrect application causes great losses. In all cases, site-specific N fertilizer field trials are necessary to determine the required amount of N in line with the expected yield. In the subhumid regions, the response to N can be dramatic. In contrast, in semi-arid zones, yield is limited by lack of water and this limits the efficiency with which N is used.

The NO_3 and NH_4 supplied in mineral N fertilizers have quite different effects in the soil-plant continuum. When taken up by crops, NO_3 causes an increased efflux of bicarbonate ions ($HCO^-{}_3$) and an increase in soil pH, while that of NH_4 leads to an enhanced proton release and a decrease in soil pH. This acidifying effect of NH_4 can be increased when a nitrification inhibitor is applied and this increased acidity can improve micronutrient uptake. In a pot experiment on sandy loam (pH 6.5) with maize and buckwheat, the use of an NH_4-containing fertilizer amended with DCD significantly increased the uptake of native soil Zn, as well as Zn applied as zinc oxide (ZnO).

2.5.2. Phosphorus fertilizers

The P in soluble P fertilizers is readily available to crops. On acid soils containing a large amount of clay, however, the soluble P can be rapidly converted into more stable P compounds and this reduces the opportunity for immediate uptake by the plant. By comparison, on the sandy savanna soils, which have a small sorption and buffering capacity, a good response can be obtained when 35 kg/ha P_2O_5 is applied to millet, sorghum or maize. Root crops, such as cassava, have a larger demand for P. Precision placement (banding) of phosphate close to the seeds or roots enhances response, while coating seeds with phosphate can help satisfy the plant's large demand for P during early growth.

In Africa and South America there are many indigenous PR deposits of sedimentary and igneous origin with a total P content of about 25% P_2O_5, such as Tilemsi (Mali), Ahoua (Niger), Red Sea (Egypt), Caldera and Mejiones (Chile) PRs. Although not all are suitable for upgrading to soluble P fertilizers, some are quite reactive, as measured by their solubility in 2% citric or formic acid. Such PRs can be used to supply both P and Ca provided that they contain only small amounts of impurities, like cadmium. The effectiveness of a PR depends not only on its reactivity but also on the degree of fineness of the particles. Finely ground PRs of high reactivity are suitable for direct application on acid soils giving a long-lasting effect of P and Ca provided that sufficient PR is applied. The efficiency of PRs can be further improved by

application adjacent to the plant rows or in planting holes so that the PR is near to the germinating seeds or developing roots. The application of reactive PRs can be considered as a capital investment because of the residual effects of the large amounts of P and Ca that are applied (Besoain *et al.* , 1999).

Field experiments must be made to test locally available PRs for the crops grown at each location. For example, Tilemsi PR from Mali containing 28% total P_2O_5 and 4.5% citric soluble P_2O_5, in experiments with maize and groundnut on an Oxisol in Gambia, gave good increases in yield. When acidulated at 30%, it gave similar yields to those given by SSP and TSP. Under upland and lowland conditions in Côte d'Ivoire with rice and legumes, the efficiency of Tilemsi PR was very near to that of TSP. Good results were also achieved with Caldera and Mejiones PRs in Chile. However, there are some PRs that have a low reactivity, and large amounts have to be applied to get a reasonable increase in yield.

Significant increases in the availability of P in PRs can be achieved by partial acidulation, i.e. by treating the PR with less sulphuric acid than the amount required to make SSP. There are other ways also. These include mixing the PR with elemental S or compacting the PR with AS to which a nitrification inhibitor has been added. They can also be added to compost of organic wastes, like straw, molasses and manure, from plant or animal production (Table 8). During microbial decomposition of the organic material, organic acids and chelates are produced. Organic acids will solubilize PRs directly and chelates will combine with Ca ions from apatites. Both processes increase P availability. Although PRs are only sparingly soluble in neutral to alkaline soils, in the presence of active plant roots, the pH in the rhizosphere can drop by 2 pH units and, in the acid conditions, the solubility of the PR, and hence plant availability of the P, will increase. To achieve such an effect, the PR must be placed near to

Table 8. Effect of composting wheat straw and phosphate rock on the percent phosphorus solubilized (Adapted from Amberger and Singh, 1994)

Treatment	% of added P solubilized after 60 days
Straw + Hyperphos (14.1 % P - 16.7 % $CaCO_3$)	14.6
Straw + Musoorie phos (8.7 % P - 20.3 % $CaCO_3$)	24.7

the roots to minimize the interaction of the P that has been released with soil components.

2.5.3. Potassium fertilizers

There is no shortage of K fertilizers worldwide and K has no adverse environmental impact. However, K fertilizers are not used as widely as they should be in many countries in the tropics and subtropics. In part, this would appear to be because an increase in crop yield has not been observed in many experiments. This would suggest that sufficient K has been available from soil reserves to meet the requirements of the crops grown. However, this process of soil mining cannot go on forever without seriously jeopardizing soil fertility and food security. Great efforts are required through knowledge transfer to bring this message to the notice of farmers, their advisors and policy makers.

Potassium is available in a range of fertilizers, some contain only K while others contain additional nutrients. Potassium chloride (muriate of potash, MOP) contains 60% K_2O and accounts for about 95% of all K fertilizers used in agriculture. It is the cheapest per tonne K_2O and mostly widely obtainable. As fine crystals it can be readily incorporated into granular compound fertilizers or it can be compacted into suitable sized particles to be spread by machine. As compacted particles it can be used in blends of different fertilizers to give required ratios of N: P: K. The use of MOP in agriculture has been recently reviewed by Kafkafi *et al.* (2002).

Potassium sulphate (sulphate of potash, SOP) contains 50% K_2O and 45% SO_3. It is more expensive per tonne K_2O than MOP but it contains two nutrients, K and S. It tends to be used for high value crops and those where it can be shown to improve crop quality, e.g. starch levels in potatoes and the smoking quality of tobacco. It can also be used to advantage on saline soils in arid and semi-arid areas. The relative effects of MOP and SOP on the yield and quality of crops was discussed by Zehler *et al.* (1981).

Potassium nitrate (NOP) also contains two nutrients, K and N as NO_3, which is readily available for uptake by plant roots. Potassium nitrate contains 46% K_2O and 13% N. Both SOP and NOP (fertigation grade) are idealy suited for use in fertigation systems because they can be obtained as very pure salts and they are readily soluble in water.

Other forms of K are sometimes used in agriculture, such as Sylvinite (21% K_2O, 26% Na_2O) and Kainite (11%K_2O, 27% Na_2O). They tend to be

used on crops that require Na like sugar beet and grass, especially that used for grazing to supply animals with essential Na.

2.5.4. Calcium and magnesium

Calcium occurs naturally as calcium carbonate ($CaCO_3$, chalk and limestone) and magnesium occurs as magnesium carbonate ($MgCO_3$, magnesite). Both carbonates are found together in dolomitic limestone. All these materials are suitable for use as soil amendments. Where these materials occur naturally, they are usually present in large amounts and it is relatively easy to maintain soils at an appropriate pH by applying them to the soil. In regions where acid soils predominate, they are in short supply and they are usually applied frequently in small amounts to soil to counter the toxic effect of free Al ions in the soil solution. Magnesium is also available in the form of Kieserite ($MgSO_4 \bullet H_2O$) or as Epsom salt ($MgSO_4 \bullet 7\ H_2O$). Kieserite is widely used as a soluble soil fertilizer because the Mg is much more available to plants when compared to other Mg sources (Härdter *et al.*, 2004). Kieserite has become a very important Mg fertilizer for oil palm production. Where it is financially advantageous to apply them as a foliar spray, e.g. to fruit trees, calcium chloride ($CaCl_2$) and Epsom salt can be used. Due to its high solubility, Epsom salt is also suitable for fertigation systems.

2.5.5. Sulphur

Sulphur can be applied as elemental S or as S-containing mineral fertilizers such as AS, ASN, SOP, Kieserite and SSP. These products have the advantage that more than one nutrient is applied. For crops with a large S requirement such as oil palm, vegetables, legumes, maize and millet, it is essential to watch for signs of S deficiency and apply S where necessary. Where subsistence farming is practised, the turnover of S through SOM is usually sufficient to meet the small requirement associated with the small yields.

2.6. Irrigation

Optimal irrigation management includes exact assessment of the amount of water required for the specific crop (which can vary between 400 and 700 mm), correct timing of the irrigation and the use of modern irrigation techniques that economize in the use of water. Many irrigated croplands suffer from the wasteful and inefficient use of water especially when farmers pay little or nothing for what they use. Excessive water use raises water tables with the risk of increasing salinity problems. Another very important aspect of a good irrigation system is a functioning drainage system. This is important but, because it has a large capital cost, it is not always installed. Drainage systems are necessary to avoid the build-up of salts in the surface soil. There are a number of irrigation technologies.

2.6.1. Surface irrigation

Surface irrigation, such as flood and basin irrigation, is the oldest and is still a commonly used method for irrigating flat land and land in shallow depressions, provided that soil structure and water infiltration rate are appropriate. The amount of water used is very large and water is wasted through leaking canals, evaporation and leaching so that the efficiency of water use is only 50% or less. Overuse of water diminishes yield and creates further ecological and environmental problems. For example, raising the water table favours the development of salinity. A variant of flood irrigation is to apply the water by means of narrow ditches, furrow irrigation. It is mainly used for crops with rows at an appropriate spatial distance, for example for potatoes, maize, sugar beet, vegetables and fruit trees. But it has the same disadvantages as those for surface irrigation. These methods are still widely used by small-scale farmers who have access to water through a network of open water canals or ditches. Water is raised to the fields from the ditches by very ancient technologies such as those based on the "Archimedes screw" or the water wheel "saiga" (Plate 3).

2.6.2. Subsurface irrigation

Subsurface irrigation applies water through perforated tubes placed at 0.5 m depth or more depending on the crop, so less water is lost by evaporation and drainage. The great advantage of subsurface irrigation is the use of smaller volumes of water, but installation costs are much greater than those for flood or furrow irrigation.

2.6.3. Sprinkler irrigation

Sprinkler irrigation is widespread with either fixed or portable systems (Plate 4). The latter are used widely depending on the topography of the land. Smaller amounts of water are used compared to surface and furrow systems but there

can be considerable evaporation and sensitivity to wind. Water use efficiency ranges from 70 to 80%.

2.6.4. Drip irrigation

Drip irrigation (Plate 5) has proved to be the most efficient method with respect to both water and nutrient use because only the rooted soil volume (Figure 8) is wetted through nozzles (drippers). The great advantage is the much smaller amounts of water required, saving 50-80%, compared to flooding, and water use is much more efficient (90-95%). As the volume of wetted soil is limited, weed development is restricted, as is destruction of soil structure at the surface, and salinity is avoided.

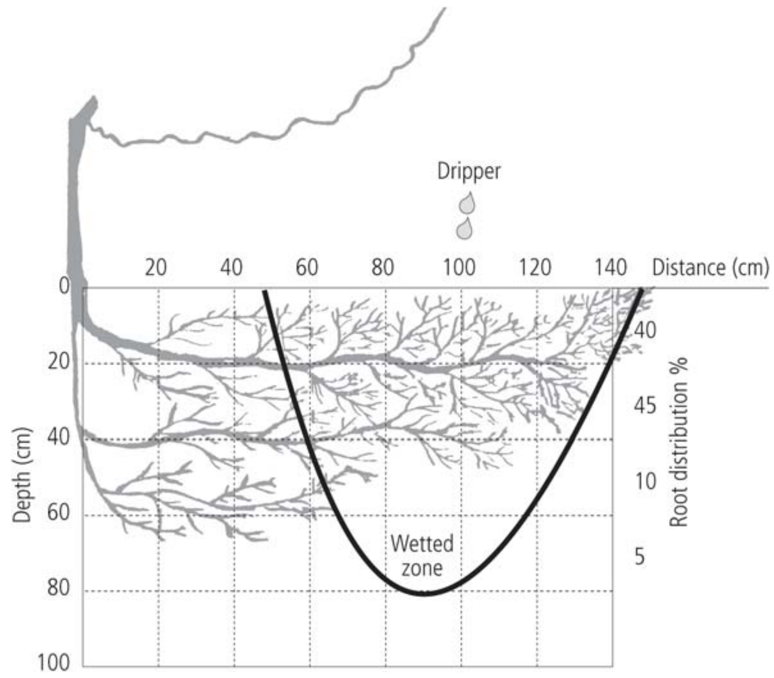

Figure 8. Vertical and horizontal distribution of Valencia Orange tree roots in relation to the wetted zone of the soil with drip irrigation (Adapted from El Fouly *et al.*, 1995)

2.6.5 Fertigation

Fertigation is a modern agrotechnique combining water and fertilizer application through drippers or microjets to meet the needs of the plant by applying them in the rooting zone. As the nutrient requirements of the plant change, the nutrient quantity and ratio can be changed easily. Completely soluble fertilizers are essential to avoid precipitation and clogging of the nozzles. It is extremely efficient and can be automatically controlled both on the field scale and in glasshouses without salinity problems. In Israel, 75% of the irrigated area is fertigated. Fertigation is used extensively in California and elsewhere. The role of fertigation, opportunities, methods and appropriate fertilizers are discussed by Hagin *et al.* (2002).

2.7. Soil and plant analysis

The total nutrient content of a soil can be measured exactly but has limited relevance to crop yield because only a small proportion of the total of any one nutrient is available to the plant. In relation to crop yield, it is now convenient to consider nutrients to exist in various pools relative to the availability to plant roots. Thus we have nutrients in the soil solution and in a readily available pool, a slowly available pool, and nutrients in soil minerals (Johnston *et al.*, 2001). Nutrients in the soil solution and readily available pools are usually measured by soil analysis. Transfer of nutrients between the soil solution and the readily available pool is rapid and reversible. That between the readily and slowly available pools is much slower but is also reversible, while release from the soil minerals can be very slow. In soils that have been fertilized over many years, reserves of P and K in the less readily available pool have accumulated from past applications of fertilizers and manures.

In developed countries, there is a long history of searching for appropriate methods of soil analysis to indicate the availability of soil borne nutrients to plants. The methods used to estimate plant availability of P, K and Mg in soil, but now increasingly for soil N also, are usually empirical. Soil analysis data, calibrated using yields from field experiments, can help classify a soil in relation to the likely response of a crop to an addition of the element being considered. Additionally, yield and soil data can be related to define critical levels of P and K in soil. Above the critical level, yields will not increase. Below the critical level, yields will be less, and a direct financial cost to the farmer. There are well-established rules for sampling soil to achieve the best results.

In developing countries, the importance of applying P to achieve acceptable yields was recognized quickly. The importance of applying K was not so clear, perhaps because experiments testing K as fertilizer showed little or no economic response to the application. The lack of response was probably because K was being released from the less readily available pool. Thus the amount and rate of release of K from this pool is very important in relation to acquiring knowledge about the need to apply K fertilizers. Unfortunately, there is as yet no generally accepted method to estimate the amount of K in the less readily available pool, yet this is important. Finding such a method for tropical and subtropical soils would be very advantageous. For practical purposes, current methods for estimating readily available K, and observation of the growing crop for deficiency symptoms, are a combined approach for assessing the need for K fertilization.

Soil testing for micronutrients can be done using a number of chemical extractants. However, to find the best extractant for a specific tropical soil is not easy, and the correct calibration and interpretation of the data are also important issues. Plant analysis tests are much more reliable and are widely used for fruit trees, oil palm and vegetables, though there are problems differentiating between the total content and the physiologically active fraction. Enzyme activities in leaves, specific to the micronutrient concerned (e.g. carboanhydrase for Zn), can sufficiently characterize the micronutrient status. A more practical concept is continuous observation during crop growth to identify possible deficiency or toxicity symptoms, complemented with soil and leaf analysis. Field trials on the actual site are usually required to confirm a deficiency and indicate the amount of nutrient to be added to overcome the deficiency.

The use of crop and soil analysis relies on having good laboratory facilities available even when soil samples are taken well. In the vast area covered by the tropics and subtropics and the great variability in crops and soils, it will be many years before sampling and analysis could become a standard practice as in many developed countries. In consequence, and for the rice crop in particular, the concept of omission plots has been developed (Dobermann *et al.*, 2002). In practice, a set of plots is established within a crop and one plot receives no fertilizer another all nutrients, including micronutrients if necessary (Plate 6). Then on the remaining plots one of the nutrients given to the fully fertilized plot is omitted in turn. From the yields it is possible to see which nutrient(s) was deficient at that particular site. In following years appropriate advice can be offered to the farmer and to the local community if the soils are reasonably uniform, on how to correct the deficiency. This method has the great advantage that large numbers of such tests can be done annually and probably more cheaply than the costly experiments required to relate yield to soil analysis on a range of sites. See also Chapter 6 on rice growing.

3. Humid tropics and subtropics

3.1. Climate, natural vegetation and cropping potential

3.1.1 Evergreen forest zone

This is close to the Equator and occupies up to a quarter of the total land area of the tropics. There are no seasonal periods. The climate is characterized by a nearly constant temperature of 25-27°C with high rainfall intensity both in amount and time. It rains practically daily throughout the year, often some 100 mm/day, to give a total of 5,000-10,000 mm/year and more. Typical are the sudden and intensive midday rains followed by very humid air and sultry conditions.

The natural vegetation is evergreen forest consisting of three canopies. On the ground there are broadleaf herbs and above these are shrubs and bushes. The final canopy consists of tall trees, sometimes with epiphytic plants, including orchids, ferns, lichens, mosses or *Bromeliacea*, as a green roof. The vegetation of the tropical rain forest has great biodiversity produced on poor soils covered with a thin layer of organic matter (humus), containing most of the nutrients in the biomass, and overlying highly leached acid mineral soils. While on the one hand, there is tremendous biomass production with a large amount of litter, on the other hand there is rapid decomposition resulting in a tightly closed nutrient cycle. These soils are totally unsuitable for annual cropping due to the large rainfall and poor nutrient status of the soil.

Examples are found in the Amazonas Basin, Congo Basin, Malaysia, Atlantic Coast of Costa Rica, Philippines, Hawaii, Cameroon, Java and the "cloud forest" of Peru.

3.1.2. Deciduous and semi-deciduous forest zones

These are found in more subtropical areas. The climate begins to differentiate between seasonal periods, e.g. a long wet season, with considerable leaching, followed by a short dry season. These forest zones are characterized by a considerable amount of litter from seasonal leaf fall. The soils in these forest zones are absolutely unsuitable for annual crop production due to the large rainfall and poor soils with only a shallow surface humic layer and very acid subsoils. However, after clearing, they can be used in a controlled and judicious way either for plantations, for example for Hevea gum or teak for timber, or a well-defined cash cropping system of intercropping and mixed cropping with coffee, cocoa, banana, tea or fruit trees and cover legumes. It is essential that the soil remains covered with vegetation throughout the year to prevent soil erosion. Often, some large forest trees are left to provide partial shading to protect the newly planted tree crops. To achieve large yields, these crops require large amounts of water and appropriate inputs of nutrients as mineral fertilizers.

Examples of such forest zones are found in West Africa (Senegal), South Africa, India, Sri Lanka and South-east Asia.

3.2. Properties of selected soil types

The typical soils of the humid tropics and subtropics, due to the high temperature and rainfall, are highly weathered. Crystalline silicates are leached out, and "weathering resistant" free oxides and hydrous oxides of Fe and Al remain. Kaolinite minerals dominate these highly weathered acidic soils. The resulting soils are red, brown and yellow loams or sandy loams of low inherent fertility with a large content of goethite and hematite, little CEC and large amounts of soluble Al.

Despite the large biomass production, the humus content of the soil is small due to the rapid decomposition of litter and continuous leaching. Depending on the topography, soil erosion by water can be ten times greater than in other climates. The direct impact of raindrops brings soil particles into suspension, removing them and the nutrients they contain. The result is strongly acid soils, poor in organic matter and plant nutrients and of low productivity.

3.2.1. Ferralsols

Ferralsols (the name is derived from ferrum/fe=iron, al=aluminium) [Oxisols, Ultisols and Entisols in the US system] are dominant in this climate. The soil is very red, red-brown or yellow in colour (Plate 7), mainly coarse textured, but some are heavy textured with more than 15% clay, finely distributed Fe oxides (goethite, hematite), Al oxides (gibbsite) and quartz. The Fe and Al oxides, with positive charge, have the capacity to fix phosphates and other anions. Ferralsols, originating from parent material poor in bases and with mainly kaolinite clays, have a small CEC and hence little cation retention. The soils are acid to strongly acid (pH 5.5-3.5) and, with decreasing pH, the concentration of soluble Al increases considerably and severely impedes root development. After land clearing, there is a rapid decomposition of the primary and secondary vegetation and, in the absence of a surface cover, the surface soil tends to become crusted (laterization/compaction) due to accumulation of sesquioxides.

Examples are found in Central Africa (Nigeria), South America (Brazil) and Malaysia.

3.2.2. Nitosols

Nitosols (derived from nitidus=shining) [Alfisols and Ultisols in the US system] are also intensely red in colour. They are fine textured soils, derived from silicate or basic material and have a CEC>20 $cmol_c$/kg and have 50% or more clay, though the clay content decreases with depth. They contain more humus than Ferralsols, a medium to large capacity to fix P and fairly good porosity, waterholding capacity and drainage, but can be acid, pH 4-5, due to intensive leaching. Geographically, Nitosols occur less widely than Ferralsols.

Examples are found in Ethiopia, East and South African Highlands, Sri Lanka and India.

3.2.3. Andosols

Andosols (derived from Jap. ando=black) [Andisols in the US system] make up about 1% of tropical soils, originating from young, volcanic glassy ashes. Grey to black in colour (Plate 8), they weather rapidly to allophanes with a large pH-dependent variable charge. They are very fertile soils. They have a large water-holding capacity, good porosity, allowing rapid water infiltration, and up to 20% SOM. The strong anion fixing capacity, mainly for P, increases with decreasing pH. However, this nutritional constraint can be partly compensated for by mulching.

Examples are found in Cameroon, Costa Rica, Japan, Java and the Philippines.

3.2.4. Vertisols

Vertisols (derived from vertere = turn) [Vertisols in the US system] are fertile, deep dark grey soils (Plate 9) with varying pH, 30-80% clay, containing smectite and beidellite, 0.5-4% SOM and a large base saturation. Typically, the soils swell and shrink depending on their moisture content. When dry, they are hard with large and deep cracks. They adsorb large amounts of water and, when saturated, they are sticky and have little porosity. The limited water infiltration is conducive to surface water runoff. Soil microbial activity is often low.

Although these soils frequently have a large total nutrient content, only a small proportion is plant-available under natural conditions due to soil physical constraints. This severely limits their production potential, especially for arable crops and, in consequence, cattle grazing features largely on these soils. The natural soil physical conditions can be improved through drainage and appropriate soil preparation but this is costly. However, if done properly, it is possible to grow rice, cotton and sugarcane, as in the Sudan Gezira with irrigation.

Examples of such soils are in West Sahel, Sudan, Chad, the black soils of Central and Southwest India, the Philippines and Argentina.

3.2.5. Fluvisols

Fluvisols [Fluvents in the US system] are soils of great variability and they are poorly developed structurally. Regionally, they are deep alluvial soils in seasonally flooded areas. They are often gleyed due to alternating reducing and oxidizing conditions in the soil. Such soils are usually used for grazing cattle or for cropping when irrigation is available.

Examples are found in the Amazon Basin and the Nile Delta.

3.3. Constraints and recommendations

3.3.1. Soil erosion

Soil erosion is a major problem but it can be lessened by using appropriate techniques (Chapter 2.4.1). Appropriate rotations would include annual cover legumes (e.g. *Cajanus cajan*, *Tephrosia*, etc.) or perennial crops of bushes or trees alternating with stripes of arable crops to maintain the water infiltration rate. It is essential to minimize nutrient losses and to increase the humus content of the soil. All these measures aim to conserve rainfall and use water in a controlled way, and to avoid erosion through adapted, sound agrotechniques and cropping systems.

3.3.2. Aluminium and phosphorus

Aluminium toxicity (Chapter 2.4.3.) and P deficiency are the major plant nutrition problems and the most yield-limiting factors in the humid tropics. Lack of available P is due either to P being chemically bound as Fe or Al phosphate, as in more sandy acid Ferralsols, or to the high fixation capacity of Fe and Al oxides and clay minerals, as in loamy Nitosols. This latter process is reversible. On the more coarse textured Ferralsols, there are good crop responses to small amounts of P fertilizers, but on the heavier textured Nitosols with their large capacity to fix P, much larger amounts of P fertilizer are needed, combined with appropriate soil cultivation strategies. In appropriate circumstances, finely ground, reactive PR can be used (Chapter 2.5.2.). Liming is important but overliming should be avoided (Chapter 2.3.3.).

Apart from choosing an appropriate P source (processed phosphate or PR) and the correct application method, genetic differences between crops and cultivars can be exploited. Both crops and cultivars differ in their tolerance to Al and Mn toxicity and soil acidity. Aluminium-resistant plants like tea or Al-tolerant plants such as cassava can withstand up to 40% Al saturation. To achieve this tolerance, plants release large amounts of chelating ions such as citrate, oxalate and malate, and phenolics or flavonoids. These exudates form stable complexes or non- or less-toxic compounds with Al ions. Identifying and introducing cultivars that have the detoxifying Al-excluding mechanism would greatly benefit small-scale farmers. Such farmers sometimes do not have access to lime and fertilizers or, if they do, they cannot afford the cost. The chelating substances released by Al-tolerant plants and microorganisms also

desorb fixed phosphates in exchange for organic anions. This also helps to mobilize insoluble Fe and Al phosphates by forming strong complexes with Fe and Al and thus releasing P that is then available for roots and microorganisms. The roots of these varieties are also associated with mycorrhizal fungi that also increase the uptake of P by roots.

3.3.3. Potassium, calcium and magnesium

In the acid soils of the humid tropics, the base cations such as K, Ca and Mg tend to be deficient. The parent material contains only small amounts and this, together with the small CEC, means that little is retained against leaching. Also they are lost in eroded soil, especially after burning the above-ground vegetation as a part of shifting cultivation. The total and available K content of the highly weathered Ferralsols is extremely small because kaolinite is the major K-bearing mineral. To produce good crops, it is essential to apply large amounts of K fertilizer to these soils. Preferably, this K is applied as split dressings during the growing season because of the risk of losses by leaching, which can be considerable. Crops respond immediately to an increase in K supply. For banana, K is the most important nutrient; deficiency leads to yellow chlorosis of the oldest leaves, “leaf fall” and “thin” fruits. On poor soils, up to 600 kg/ha K (mainly as KCl) is recommended for high yielding varieties due to the large export of K in the fruits. Also Hevea and oil palm have a large requirement for K.

Vertisols, rich of clay (>30%) and with a large CEC, have smectite and vermiculite as the dominant K minerals. In this case, K retention in forms that are not immediately plant available is a problem that increases with clay content and the depletion of soil K over long periods. In this case, the amount of K applied must be increased above the normal practice and applied at sowing or planting to increase the available K in the soil solution.

On alluvial Fluvisols, nutritional constraints are due more to imbalances between the base cations than to deficiencies. These imbalances are caused by parent material, cropping system and degree of depletion by leaching and cropping. Calcium and Mg deficiencies are very common in the acid soils of the humid tropics due to poor parent material, small CEC and intense leaching.

3.3.4. Nitrogen and sulphur

All cash crops have a large N requirement and N deficiency is widespread in the humid tropics due to considerable losses of NO_3 by leaching. Conserving SOM and growing leguminous crops within a crop rotation, as well as applying adequate amounts of N fertilizer, are essential to achieve good yields. In these regions, both urea and AS are widely used because CAN is deliquescent.

Sulphur deficiency is becoming more frequent due to reduced S emissions to the atmosphere, leaching and to sorption of sulphate (SO_4) ions on sesquioxides in the soil, particularly in Ferralsols, but also due to desorption of SO_4 as a consequence of increased applications of P fertilizers. Sulphur can be applied in various ways (Chapter 2.5.5).

3.4. Land use and farming systems

3.4.1. Evergreen and deciduous forest

The agricultural use of existing evergreen forests has to be rejected for climatic, ecological and economic reasons. The great biodiversity of the natural vegetation should be carefully preserved and protected. However, a judicious, strictly controlled and selective use of the valuable tropical woods, such as mahogany and varieties of cypresses, could be allowed if followed by responsible replanting and maintaining a vegetative cover. Rather than leaving "untouched tropical forest", there should be a policy of well-balanced, sustainable use that maintains natural resources and the great biodiversity of this unique ecosystem. A total boycott of harvesting tropical woods will not help solve the social and economic situation of the poor people in these regions. Limited land for settlement has to be cleared for small-scale subsistence farming by the inhabitants of the forest. Areas with deciduous or semi-deciduous forest in subtropical climates that change into the humid savanna, offer great potential both for plantations of fast growing, valuable tropical woods, like teak and eucalyptus. In addition, cash crops such as coffee, cocoa, banana, vegetables and fruits could be grown for sale in local markets. Such systems can run in parallel with subsistence farming by small-scale farmers using appropriate rotations, including legumes. A vegetative cover with suitable crops should be maintained throughout the year to avoid erosion.

The risk of soil erosion can be estimated by determining the percent of the rainfall that appears as water run-off. The percent is small (1.3-1.7%) and independent of slope under a forest canopy. But with maize grown in the absence of an organic mulch, percent run-off can increase to 40-43% on 5 and 10% slopes, respectively. Mulch will decrease these losses to 6-8% (Bornemiza and Alvarado, 1975).

3.4.2. Shifting cultivation

"Slash and Burn", adapted to the conditions of the humid tropics, is the old pioneer system of land use (Plate 10). With shifting cultivation, a small piece of cleared land is used to grow food for some years. When the returns in terms of food production no longer justify the effort required to grow the crops, the land is allowed to revert to natural vegetation and another piece of land is cleared to grow crops. Through the land clearing process, the originally closed nutrient cycle is interrupted. Most of the mineral elements in the vegetation are retained in the ash, though this is at risk to loss by wind and water erosion, and there can be a moderate increase in soil pH. The major part of carbon (C), N and S is lost to the atmosphere. The cleared, bare and unprotected soil is at great risk to loss by erosion.

The advantages of "Slash and Burn" are the low investment cost and reduced weed growth and crop diseases. However, the return of plant mineral nutrients via the ash is small and, with no or little external inputs, yields decline rapidly. At least six years of fallow are necessary for regenerating soil fertility through natural vegetation. Microbial activity in the surface soil, which is depressed only partly by heat sterilization, regenerates rapidly. As long as the fallow period lasts for 6 to 10 years, the system can be justified primarily for subsistence farming. However, under increasing population pressure, fallow periods tend to be shorter than is ideal, causing declining productivity, and this makes this traditional system ecologically unsustainable.

"Slash and Mulch" ("zero burn technique") is a fire-free land preparation through slashing, chipping and mulching (Denich *et al.*, 2002). It is a promising alternative for sustainable subsistence agriculture. Instead of burning the above ground biomass, the shrubs and woody vegetation is repeatedly chopped by a tractor-driven bush chopper, and the chippings are broadcast over the soil surface. The subsequent microbiological decomposition of the mulch promotes the release of nutrients into the soil, avoiding gaseous, leaching and erosion losses and improving the nutrient balance in the soil.

However, the large C:N and C:P ratio and variation in the lignin content of the chopped vegetation from the different species, requires the addition of some N and P fertilizers to counteract immobilization of soil N and P during microbial decomposition of the added biomass. Additional N, P and K fertilization will be required to achieve reasonable yields. Burning favours the subsequent development of grassy vegetation, whereas woody vegetation is promoted in the fire-free system.

With the slash and mulch system, a fallow period of 3-4 years is possible. This would allow small-scale farmers to use the land more intensively with moderate fertilization in an appropriate cropping system. The decision on which system to use and which crops to grow depends on the availability of machinery and on whether cash crops are produced for sale or are only for the farmer's family and animal feed. Various combinations of cropping are possible. Crops can be grown singly, with larger inputs and yields, or mixed, to reduce risks. Intercropping can include cereals (wheat, maize, rice), tubers (yam, cassava) and legumes (cowpea, pigeon pea), but also fast growing crops for green fodder or manuring (*Acia barteri*, *Clorophira excelsa*, *Aldornea cardifolia* and many other species) or in combination with tropical grasses (*Pennisetum purpureum*, *Panicum maximum*). *Crotolaria juncea* or *Pueraria phaseolides* may also be used. All these green manuring crops produce substantial amounts of biomass for incorporation into the soil to increase SOM, supply nutrients and improve soil structure. Shrub legumes, *Cajanus cajan*, *Leucaena leucocephala* and *Vigna radiata*, are particularly recommended because they fix large amounts of N. Additional P fertilizers will give good yields when applied in bands along the rows.

3.4.3. Alley cropping

This is an advanced form of agroforestry in which food crops are planted in the alleys (inter-row area) between lines of trees, shrubs or leguminous crops. Alley crops, such as maize, millet, cassava or grasses are grown between rows of perennial trees, such as *Azadirachta indica* (the neem tree), *L. leucocephala* or *Gliricidia sepium*, from which leaf material can be taken for mulching, or shrubs such as *C. cajan*, that form hedges. The deep-rooting system of such perennial trees or shrubs can bring nutrients from deeper layers of the soil up to those layers where they can be taken up by the roots of agricultural crops, i.e. a form of nutrient cycling.

3.4.4. Arable cropping

In the humid tropics, the productivity of arable cropland is very dependent on fallow management. Suitable crops to grow in rotation are legumes and grasses. Low input, small-scale subsistence farming with cereals (maize, sorghum, upland rice), tuber plants (yam, cassava) and grain legumes is practised by farmers feeding their own families and growing fodder for animals. High-yielding cash crops, such as coffee, cocoa, banana, tea, oil palm and fruit trees require a large input of fertilizers, crop protection products and intensive soil preparation. Permanent monocultures should be avoided. Legumes play an important role in this system both for human consumption and for soil fertility. Additional fertilization conserves or improves soil fertility. Rice is becoming a main staple food in West Africa, mainly in the uplands but also on rainfed lowlands with continuous cropping on the same field over several years.

3.5. Summary

The main constraints to productivity in the humid tropics are soil erosion, Al toxicity and N, P and K deficiencies on very poor acid soils. Whereas the deciduous or semi-deciduous forest offers a great potential both for timber and cash crop production as well as for small-scale farming, the unique ecosystem of the tropical evergreen forest should be carefully protected and agricultural use, if allowed, carefully controlled.

Shifting cultivation with land preparation by slash and mulch is superior to slash and burn because it retains nutrients and organic matter in the soil, improving soil fertility, and allows shorter fallow periods with moderate fertilizer inputs. Management practices must concentrate on the return of crop residues to minimize soil erosion.

4. Semi-humid and semi-arid tropics and subtropics – rainfed savannas

These zones account for about 60% of the total land area in the tropics and subtropics. They are characterized by the amount and variability of both precipitation and soil types, which differ in fertility partly due to human activity. They include the sub-Saharan belt from Senegal to Sudan, parts of southern Africa, large parts of India and the typical South American savannas.

4.1. Climate and natural vegetation

In general, the amount of seasonal rainfall decreases with increasing distance from the Equator and, this combined with longer dry seasons, finally results in arid zones. There are unimodal and bimodal rainfall patterns with one or two rainy seasons (March to July and September to November), with rainy seasons lasting for 4.5-7 months in the semi-humid tropics and 3-4.5 months in the semi-arid tropics. The total amount of precipitation varies widely between 200 and 1500 mm/year. The greater part of the annual rainfall comes within 5-10 days resulting in surface water runoff and severe soil erosion depending on slope and soil texture. In the semi-humid areas, precipitation can be sufficient for some crops for a few months, but in the semi-arid areas evapotranspiration can be as large as 200 mm/month, due to the intense solar radiation and high temperature, and this can exceed precipitation.

The natural vegetation, known as savannas, consists mainly of grasses, herbs and shrubs, occasionally with small groups of trees or some patches of natural semi-humid/semi-arid dry secondary forest. There are three types of savanna vegetation.

4.1.1. Moist, tall grass savanna

With 600-1500 mm rainfall per year in the subhumid Guinea zone (South Ghana, Benin, Nigeria) the grasses, *Pennisetum, Andropogon, Hyparrhenia, Panicum* and *Imperata*, form a dense canopy during the rainy season. This savanna type is widespread in Africa and has considerable potential for rainfed farming.

The Cerrados of the great Brazilian plateau consist of semi-deciduous forest with trees and shrubs with an undercanopy of grasses and small herbaceous plants. When taken into crop production, soil organic matter decreases rapidly. On the Colombian Llanos, short grasses, such as *Trachypogon* and *Axonopus* are dominant. The rainy season is between October and April, with 500-1500 mm/year, and with temperatures of 19-26°C.

4.1.2. Acacia low grass savanna

With rainfall <600 mm/year, the bush steppe of the sub-Sahel zone consists mainly of tussock grasses and low bushes. This savanna type is found in the semi-arid Sudan where nomadic grazing has been practised historically.

4.1.3. Acacia dry grass savanna

With only sporadic rainfall, 50-200 mm/year, these grass steppes have deep-rooting grasses as well as thorny succulent shrubs and are typical in the sub-Saharan area. They represent the transition to really arid vegetation. Only very limited nomadic grazing with small ruminants on native pastures is possible. In more humid locations there can be some small-scale subsistence farming with barley and vegetables.

4.2. Properties of selected soil types

The soils in semi-humid/semi-arid areas are very varied because they are derived from a range of parent materials.

4.2.1. Ferralsols, Luvisols and Acrisols

Ferralsols, Luvisols and Acrisols [Oxisols, Alfisols and Ultisols in the US system respectitively] are found in the savannas of West Africa and South America. They are strongly weathered, mainly coarse textured sandy/loamy soils with kaolinite as the major clay mineral. Water infiltration is rapid and water-holding capacity is poor. These soils have little SOM and small CEC and are highly leached. They are very sensitive both to drought and erosion. They are inclined to compaction and, occasionally, lateritic pans are formed. The colour varies depending on the state of hydration of the ferric oxides. They are acid to very acid and are P, K, Mg and Ca deficient. When pH is <5.0, there is associated Al toxicity. Acrisols have a large content of extractable Al. More fine textured Acrisols and Luvisols occur in East Africa with lessivation and clay enrichment in the subsoil. The main clay mineral is illite and there is only a small content of Fe and Al oxides.

In these soils, termites play an important role in soil fertility. They live in typical turret-like constructions and rapidly decompose plant residues accumulating lignin components, the primary constituents of stable humus.

4.2.2. Red coloured Nitosols

The red coloured Nitosols [Ultisols and Alfisols in the US system] are found frequently in West and South Africa, India and Sri Lanka. They are fine textured soils with a base saturation of 35% and a large clay content, mainly kaolinite. They are poor in silicates, nutrients and organic matter and Al toxicity occurs on the more acid soils. Phosphorus deficiency is common due to the large P fixation capacity on Fe oxides and clay minerals. For example, Bako, a soil found in Ethiopia, had pH 4.6 and a total P content of 5,630 mg P/kg soil but <1 mg P/kg was plant available. Compared to the Ferralsols, the Nitosols have a smaller water permeability due to clay accumulation at depth.

4.2.3. Cambisols

Cambisols (Ital. cambiare) [Inceptisols, Ultisols in the US system] are brown in colour, sandy to loamy in texture and the base content and soil reaction depend on the parent material. They are weakly developed, of good structure and well-drained with pH>5.0 and a CEC>16 $cmol_c$/kg soil. Where illite is a major clay mineral, K is readily retained in non-exchangeable forms.

Examples are found in the more gleyic (Indus Delta) and the intensively used semi-arid soils (Dekkan Plain, India, North Africa).

4.2.4. Kastanozems and Planosols

Kastanozems and Planosols [Mollisols and other suborders in the US system] are often fertile, black in colour with a large organic matter content. They have a medium to high base saturation and neutral pH. In India, they are derived from basalt or carbonate-containing loess rich in organic matter. In depressions in the landscape in subhumid regions, as in the Argentinean pampas and Uruguay, they have considerable potential for growing wheat, maize and oilseeds. These soils also occur in limited areas in the north and south of the Sahara plains.

4.2.5. Leptosols

Leptosols (derived from the Greek leptos=shallow) [Mollisols, Entisols in the US system] in the Mediterranean area are shallow soils (Rendzinas) on limestone (Plate 11). They are rich in organic matter and basic material, but have little water holding capacity. The time of seeding and fertilization are important and should be just before expected rainfall. These soils form the transition to the Aridisols of arid climates, and are discussed in the following chapter.

4.2.6. Vertisols

Vertisols [same in the US system] are dark or grey coloured, heavy-textured fertile soils with a neutral to alkaline reaction and large production potential. They cover the great plains of India (Dekan basalt plateau), Argentina and Uruguay, and they are typical of riverbank areas, e.g. Chad basin and the Gezira in Sudan. These soils have 30-80% clay, including montmorillonite and smectite, and have a high base saturation and a pH 5.5-6.5. When wet, these soils swell becoming plastic and sticky but, when dry, they shrink strongly forming deep cracks. Despite their large total nutrient content, the available P and K is very small, especially with increasing soil dryness. The large total CEC of the soils rich in smectite and vermiculite explains the large K retention capacity. The heavy texture, considerable water holding capacity and poor drainage are the predominant physical constraints to productivity. Normal arable farming is very difficult and requires large inputs of organic matter and N fertilizer because of denitrification losses, as well as investment in drainage. Often there is grassland without irrigation. On the Gezira plains (Sudan), agriculture on soils with 30-60% clay has primarily focussed on irrigated cotton. But because of increasing physical and chemical difficulties, as a result of monocropping, there has been a continuous decline in yields despite large inputs of mineral fertilizers and investment in mechanization. Productivity has increased with the introduction of improved rotations - including cotton, groundnut, sorghum and fallow.

4.3. Constraints and recommendations

Appropriate soil management is essential when soils in the semi-humid/semi-arid tropics and subtropics are used for agriculture. Even with intensive farming, soil fertility can be sustained and possibly improved by good management practices. However, mismanagement can lead to soil degradation.

4.3.1. Wind erosion

Wind erosion on sandy soils is the most important form of soil degradation. In semi-arid areas, soil aggregates of poor stability are transported by wind and severely physically damage plants in their early growth stages. Furthermore, wind erosion removes smaller soil aggregates and this leads to a reduction in the water holding capacity.

4.3.2. Drought

Drought is a major constraint in semi-arid regions with long dry seasons (Chapter 2.4.2.). Minimum tillage and moderate soil preparation decrease evaporation. Covering the soil surface with a mulch of crop residues benefits soil water holding capacity and rainwater conservation. Seeding just before rainfall is expected is a further valuable measure against the damaging effects of drought.

4.3.3. Overgrazing and deforestation

Savanna areas with little rainfall and poor soil fertility can support natural grassland for grazing by livestock. However, under the pressure of rapid population growth, human food demand is increasing and this is leading to an excessive number of animals overgrazing permanent pasture on marginal soils. Wherever the protective vegetative cover is destroyed, the bare soil is at great risk to erosion by wind and water, which finally results in total desertification, and consequent human migration.

The growth of natural savanna grassland is limited due to lack of rainfall and a long dry season. Pasture production can be plentiful during the wet season but, during the dry season, little forage, often of poor quality, is produced. In Africa and in South America, large savanna areas are burnt during the dry season, resulting in considerable losses of organic matter and nutrients. After burning, the land is planted with pasture grass (*Brachiaria*), which is readily accepted by ruminants and gives high yields with N fertilizers. Excessive cultivation, frequently after burning, of sensitive silty soils with heavy machinery at inappropriate times leads to compaction and crusting, and this greatly decreases yields. Vulnerable soils should be cultivated very cautiously and supplied with organic matter such as a mulch of plant residues or manure. Where pasture follows deforestation and the pasture is overgrazed, there is a considerable loss of organic matter. This can lead to desertification if inappropriate methods of land use follow. Trees and shrubs are cut down and sold as firewood, because this earns a good price on the local market. Thus, large scale clearing of intact woodland is widespread, but usually there is no replacement of the trees or establishment of new plantations.

Overgrazing and deforestation favour a steady progression to desert. The strategy of stopping this process focuses on re-establishing the vegetation of rangeland, strictly defining areas for collecting firewood and protecting the remaining trees against animal grazing. The restoration process must start with improved grazing practices, where it is allowed, with only an appropriate number of livestock, followed by fallow periods for the restoration of soil fertility. In the restricted areas, trees have to be planted and protected. Based on soil surveys, suitable regions have to be defined for pasture, woodland, subsistence farming, agroforestry and food production. This is a matter for management by the local community.

4.3.4. Phosphorus and aluminium

In many of the soil types found in the semi-humid/semi-arid tropics, the total P content is very small and is mainly in organic compounds. This lack of P is one of the major factors limiting yields. Compared to soils in humid tropics, Al toxicity is less common and usually found only with very acid Ferralsols. These soils are found in the Colombian Llanos, with 500-1,500 mm rainfall. They are rich in amorphous Fe and Al oxides, have a pH between 4.5 to 5.5 and an Al saturation of 70%.

In the acid sandy Ferralsols and Acrisols, which developed from granite and quartzite, phosphates occur as insoluble Fe and Al phosphates (Figure 9). With increasing pH, the concentration of free Fe and Al ions decreases and that of Ca ions increases, and phosphates occur as $CaHPO_4$ and as hydroxyl and fluorine apatites in Cambisols, Kastanozems and Rendzinas. In the Nitosols with a large clay content, phosphate ions are absorbed on Fe and Al oxides and desilicated amorphous material of variable charge. The phosphate fixing capacity increases when the ratio of Fe oxides to clay >0.2, and decreases with increasing pH. Hydroxyl, bicarbonate, organic and silicate anions compete with phosphate ions for the binding sites on the soil particles, and P fixation decreases with increasing humus content.

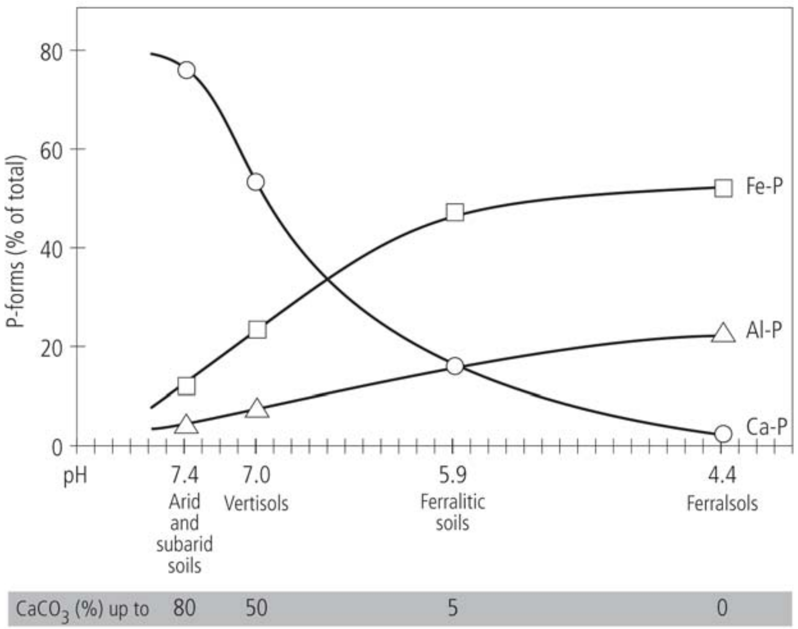

Figure 9. Percent iron, aluminium and calcium phosphates in different soil types related to percent calcium carbonate

4.3.5. Nitrogen and sulphur

Nitrogen deficiency is widespread and a major yield-limiting factor. Symbiotic and non-symbiotic N fixation, plant residues and animal and human wastes are the main sources of N for plants in the absence of N fertilizers. The total N content of the soils in the semi-humid/semi-arid tropics and subtropics depends on their content of SOM, the more stable forms of which also play an important role in retaining water, and the retention of nutrients in plant available forms. Therefore, increasing the SOM content should be a main priority. Soils developed from granite or quartzite naturally have a very small content of SOM. Grassland savanna soils have a high C: N ratio and hardly release any N for plant uptake. During the dry season, NO_3 accumulates in Alfisols and, at the beginning of the wet season, there is a large flush of mineral N. However, the largest part of this N will be lost by leaching and through erosion because only a small percentage is used by annual crops.

Fertilizers have to be applied at the correct time using the right application method. In semi-arid regions, urea and CAN are usually used having replaced AS, because AS acidifies the soil. The conversion of urea to NH_3, due to urease activity at the high temperature in the tropics and subtropics, takes place in a few days. The subsequent oxidation to NO_3 depends very much on soil pH; 1-2 weeks in neutral/alkaline soils and 3-4 weeks in acid soils.

Sulphur is not a major problem in less intensive traditional cropping systems but may be with high yielding crops. Sulphur is often deficient in light textured, highly weathered soils that are poor in organic matter, the only source of S, because of continuous burning of the vegetation, as well as adsorption of SO_4 on Fe and Al oxides and on any weathered edges of clay particles. Experiments with oilseeds, oil palm, legumes, vegetables and maize showed good responses to application of S in West Africa (Table 9). Ammonium sulphate, SSP, SOP and elemental S added to TSP or to PR can meet the S requirement of many crops.

Table 9. Effect of sulphur fertilization on crop yield in selected countries in West Africa (Adapted from Kanwar and Mudahar, 1986)

Country	Crop	% yield increase due to S fertilization
Senegal	Groundnuts	6
Burkina Faso	Sorghum	14
	Cowpea	38
Niger	Groundnuts	6
	Pearl millet	11
Togo	Groundnuts	45
Benin	Groundnuts	35
	Maize	32
Nigeria	Maize	45

4.4. Land use and farming systems

4.4.1. Natural pastures

Natural pastures occur on sandy soils, foothills and slopes that were originally shrub steppes or woodland. With 250 mm or more rainfall per year, natural pastures provide useful grazing for small ruminants but, under communal ownership, they rarely support livestock on a year-round basis. A barley/fallow rotation without any input provides additional livestock feed. For example, *Brachiaria* grows in Brazilian pastures with a small input of mineral nutrients from ashes after cutting and burning the forest.

Natural grass cover, including some legumes, responds economically to 25 to 35 kg/ha P_2O_5. Sowing or drilling legumes with a small amount of molybdenum (Mo), or Mo-prilled seeds, improves the nodulation of legumes and produces better pastures. Grass species differ widely in their tolerance of acidity. *Hyparrhenia rufa, Melinis multiflora*, *Brachiaria decumbens*, which are grown on soils containing more moisture, and *Pennisetum purpureum* (elephant grass), *Stylosanthes humilis* and *Desmodium intortum* are all tolerant of soil acidity. However, the fast growing *Leucaena leucocephala*, *Trifolium repens* and *Medicago sativ*a are susceptible to soil acidity (Sanchez, 1976). A serious constraint to adequate production on these soils is soil degradation through overgrazing.

With more rainfall and for more intensive grazing, fertilization with N and P is necessary on acid soils, such as on the Colombian Llanos and the Brazilian Cerrados with pH 4.5 to 5.0. Liming with approximately 5 t/ha dolomitic material improves growth significantly. Also, ley farming, alternating arable crops with legume-based pastures is possible. Fertile soils in semi-humid zones have considerable potential for intensive dairy farming, but large-yielding grasses, such as *Pennisetum purpureum*, *Setaria sphacelata* and others, require fertilization. For example, in Uruguay, Argentina and southern Brazil, the application of 200-400 kg/ha N, 150 kg/ha P_2O_5 and 200 kg/ha K_2O complemented with applications of S and Zn, is practised. However, the use of mineral fertilizers should be related to expected returns.

4.4.2. Arable cropping

With arable cropping, the soils become very susceptible to erosion, and more attention to fertilization is required. There are different cropping systems in

use, depending on the prevailing rainfall, soil conditions and socio-economic conditions.

In rainfed subsistence farming, cereal crops such as barley and wheat predominate with inputs depending on soil fertility. Organic manuring and legumes are important factors in these cropping systems. A surface cover, plant residues or mulch, absorbs the impact of raindrops reducing surface water runoff and erosion and preventing soil compaction and crusting on structurally weak soils.

In semi-arid regions, crop rotations are based on food crops such as sorghum and millet with only small inputs. In semi-humid areas, these low-input rotations are based on cassava, plantain or rice, with larger inputs of fertilizer and lime for maize and yam.

With an annual rainfall of 350-600 mm and on more fertile soils, wheat-based rotations predominate with bread wheat or durum wheat as a staple food. Wheat/fallow or wheat grown in rotation with a legume, such as chickpea, lentil or faba bean is recommended. Other possible rotations that require balanced application of mineral fertilizers, include cotton/sorghum or cotton/maize with summer crops such as sunflower, an important edible oil plant in Mediterranean regions. Cotton needs special attention because of its large nutrient requirement, especially for K. The critical K concentration in leaves is about 0.9 % in dry matter. Crop residues may be used as feed or mulch.

Continuous monocropping with arable crops, even with large fertilizer inputs, can lead to decreasing yields and soil deterioration with increasing surface water runoff, leaching, erosion, poor rooting and escalation of pest problems.

Pearl millet, sorghum, cowpea and groundnut are the main crops grown by subsistence farmers in the Sahelian zone (Niger, Sudan). Table 10 shows that with a small input of fertilizers, the yields of both pearl millet and cowpea are greatly increased. In some cases, similar increases were also achieved by incorporating crop residues. However, the combination of fertilizers and crop residues gave by far the largest yields. Incorporating crop residues not only recycles plant nutrients but also increases the CEC, which retains cations in plant-available forms.

The intensification of arable cropping on the savanna soils of South America is constrained by soil acidity and poor soil fertility, mainly deficiency

Table 10. **Effect of fertilizer and crop residue on the total dry matter yields (kg/ha) of pearl millet and cowpea fodder (Adapted from IFDC, 1994)**

Treatment	Pearl millet		Cowpea fodder	
	1993	1994	1993	1994
Control	1,238	813	840	1,063
Crop residue (CR)	3,209	1,663	893	2,363
Fertilizer (F)	3,481	2,375	2,010	2,250
CR + F	6,393	5,204	2,400	6,421
LSD 0.05	1,650	738	390	952
CV (%)	29	18	16	20

of P and Mg. Recommendations to overcome these constraints are judicious liming or growing acid tolerant cultivars and appropriate inputs of fertilizers. Rotations can include grain legumes (e.g. cowpea), green manuring and pasture ley. Rice-based systems require only moderate liming, whereas maize-based systems need larger amounts of lime (2 t/ha). Rice/cowpea or maize/soybean rotations are also possible. In either case, applying 40-80 kg P_2O_5/ha gives good results.

Mixed cropping, which is widely practised in subsistence farming without any fertilizer, consists of the simultaneous growth of cereals and mainly legumes on the same field. This decreases the risk from lack of rain and low soil fertility by improving the utilization of soil nutrients through the differences in temporal or spatial growth of different plants.

Various systems of intercropping are practised depending on climate and soil conditions. The major crops include cassava, sweet potato, rice, maize, sorghum, millet, pigeon pea and sago palm. The combination of maize and cowpea is very common. Without nutrient inputs, the productivity of intercropping is relatively small, because both crops compete for available nutrients, but the permanent soil cover minimizes soil erosion. Maize and cowpea cropped alternatively is much more productive than intercropping.

Many legumes, with high-quality protein for humans and animals, can be grown as intercrops. These include among others, cowpea, chickpea, pigeon pea, green gram, black gram and groundnut. Legumes with a short growing season, such as *Pueraria phaseolides*, *Stylosanthes humilis* and *Mucuna utilis*, both fix atmospheric N and provide good surface mulch. The latter helps lower topsoil temperature, conserve moisture, improve soil structure, accumulate organic matter and favour an increase in earthworms and soil microorganisms. In summary, crop rotations of cereals alternating with legumes seem to be the most appropriate alternative to extensive bush/fallow systems, but also different forms of intercropping can be a good practice.

Alley cropping can be used where there is sufficient moisture, using various combinations of food crops and leguminous tree and shrub species like *Leucaena leucocephala*, *Gliricidia sepium* or *Acacia saligna* (the latter under more semi-arid conditions). Trees in rows at 3-4 m spacing provide shade, litter and a good windbreak. Trees and shrubs favour a better utilization of soil nutrients than does intercropping. However without any applied fertilizer, the yields will remain relatively small.

In Burkina Faso, there is an interesting method for the restoration of degraded dryland. Holes 10-20 cm in diameter and 10-20 cm in depth are dug in the crusted soil and filled with two handfuls of organic residues from plant or animal production. Sorghum is then sown before the beginning of the rainy season. Rainwater collects in the holes and the concentrated nutrient supply greatly increases yields on these very marginal soils without any large fertilizer input.

Generally, yields and the way they fluctuate, depend primarily on the availability of water, even in humid zones, and fertilizer inputs. A limited yield potential requires an appropriate nutrient input. Crop rotations play a major role in fertilizer management. The response to N is twice as large in wet years than in dry ones. Response to P and K depends on the chemical properties of the soil and the crop requirements. Improved crop varieties need larger amounts of nutrients. Placement of P fertilizer together with the seed results in its immediate availability to the growing roots. Row or band application of P fertilizers also has substantially better effects on yield than broadcasting.

4.5. Summary

The natural productivity of the semi-humid/semi-arid rainfed savanna zones depends on the amount and distribution of rainfall as well as on soil fertility. For agricultural production, the major ecological constraints are soil erosion, drought, overgrazing, deforestation, soil nutrient mining and nutrient imbalances. Phosphorus and N are the nutrients that are usually deficient, followed by K and sometimes Mg depending on crop requirement and cropping intensity. Phosphorus fixation depends on the amount of Fe and Al oxides. With increasing clay content in the soil, especially if the main mineral is smectite, K retention may increase in forms not immediately plant available and this increases the requirement for K fertilizer. Screening of crops and cultivars that are able to acidify the rhizosphere through the release of protons and improve nutrient availability through excreting chelating organic acids presents the opportunity for a forward-looking strategy for controlling P and micronutrient acquisition. This is very important particularly for low-input farming systems, but cannot continue indefinitely because soil nutrient supplies are being mobilized and used.

For sustainable agriculture with large inputs of manufactured fertilizer, a well-planned rotation is required to conserve and improve soil fertility, but also to increase farmers' income. The overall aim of applying fertilizers and organic manures and managing crop residues is to maintain or improve soil fertility and thus increase agricultural production and improve product quality. In the semi-humid/semi-arid regions there are risks to agricultural production but, also, there is the possibility for an increase and stabilization of biomass production.

5. Arid tropics

5.1. Climate and natural vegetation

Arid zones in the tropics cover about 16 % of the total land area. In Africa, these are the Sahel and Sahara, and the Kalahari desert in the south. Arid zones are found also in parts of Asia, including large parts of Central India, Australia and South and Central America.

Compared to the semi-arid areas, where precipitation is insufficient for several months, thus limiting crop production, in the arid tropics, the total annual precipitation is only sporadic and very small (<200 mm), and it is combined with a very large evapotranspiration for the whole year. One or two mild, wet winter months can follow very hot summer months with high solar radiation and great differences in temperature between day and night. The

large differences in the amount and distribution of the rainfall are illustrated as follows: In Sudan, there is one very short period of rainfall in summer with temperatures between 40 and 50°C. By comparison, in Mexico and Arizona, there are two short rainy seasons. In Israel and the Sahara, most of the annual rainfall is in one short period, which is followed by a long dry summer. In the dry period, strong winds can be a serious problem creating sandstorms.

Low grass savanna is the dominant natural vegetation in the semi-arid and arid steppes. A poor, scanty grass cover is produced during short growing periods and this dries out completely later in the year. Nomadic grazing with migrating herds is common. For any subsistence arable farming, a minimum of 250-300 mm annual rainfall is needed.

With decreasing precipitation, there is a transition from the "Half Desert" to the "Desert" vegetation. This consists of very poor grasses and thorny, drought resistant shrubs (*Tamaricaceae, Euphorbiaceae*, *Chenopodiaceae*) that grow with very little or sporadic rain and high temperatures (Plate 12). Xerophytic and succulent plants (*Crassulaceae*) can store water in the leaves or stems (e.g. *Adansonia digitata*). They also possess a special mechanism to utilize CO_2 very efficiently. Halophytic plants use sodium chloride (NaCl) for maintaining the turgor of the cells.

In the extremely arid desert, there is no vegetation at all but, with irrigation, the land can be used successfully for agriculture. In oases in the deserts, plants and trees grow with partly saline water.

5.2. Properties of selected soil types

In these arid regions, the soils are commonly alkaline (pH>7) but their other properties vary widely. There are gravelly or sandy steppe desert soils but also alluvial soils near the larger rivers. After heavy rains, dry valleys (wadis), can be occasionally flooded with fast flowing water and become very dangerous. The type of soil depends on the parent material and weathering intensity and this influences possible agricultural use. Physical rather than chemical weathering of soil minerals predominates due to the high temperature and lack of water. As there is no leaching, the soils contain Ca and Mg carbonates, which are practically insoluble, and SO_4 so that the soils have a neutral to alkaline reaction. Nutritional constraints are directly related to the large bicarbonate concentration in the soil solution. Due to the permanently large potential evapotranspiration, soluble salts, mainly NaCl and magnesium sulphate

($MgSO_4$) rise within the soil with irrigation and precipitate at the soil surface causing salinity problems.

5.2.1. Chernozems and Kastanozems

Chernozems and Kastanozems [Mollisols in the US system] are fertile soils, grey-black or red-brown in colour. They are the typical steppe soils, developed from carbonate loess and unweathered silicates under subhumid/semi-arid grassland climates with high summer temperatures. They are high in base saturation and organic matter and have a neutral pH. Examples are found in Central India, Peru, Argentina, Eurasian steppes, and also partly in the north and south of the Sahara desert.

5.2.2. Red-brown Mediterranean Rendzinas

Red-brown Mediterranean Rendzinas [Mollisols in the US system] are shallow soils overlying carbonate material. The soils are frequently crusted and contain many stones. They have a large content of bases and organic matter but only a small amount of K-bearing minerals. They have developed through physical and chemical weathering in a climate with 100-180 mm rain per year. Little water storage and restricted rooting pose severe problems but, when properly managed, these soils can be fairly productive. Examples are found in areas around the Mediterranean Sea.

5.2.3. Xerosols and Yermosols

Xerosols and Yermosols (derived from Greek xero=dry and Span. yermo=desert)[Aridisols in the US system] are the soils of half desert and desert, and are yellow to brown in colour. The silicate minerals (quartz), which are very little weathered, are coated with a film of oxides of Fe and Mn, so called "desert lac", and when eroded the soils have a crusted surface. Generally, they contain a lot of free carbonates (up to 80 %) and are neutral to alkaline in pH, but are extremely low in organic matter and all plant nutrients. When irrigated and fertilized, they can be very productive. Chloride, bicarbonate, SO_4 and NO_3 are the predominant anions in the soil solution. Soluble Na, Ca and Mg salts are transported to the soil surface due to the high evaporation and tend to be precipitated at the surface preventing plant growth. Examples are found in Morocco, Libya, Egypt, Jordan and Saudi Arabia.

5.2.4. Fluvisols

Fluvisols [Entisols in the US system] are fertile soils found in valleys and the deltas of large rivers (e.g. the Nile and Euphrates). They are formed from alluvial deposits with some thick layers of sand and silt, and are periodically flooded or irrigated. They vary widely from sand to loam and clay and also in the quantity and type of clay minerals. The latter has consequences for both K release and retention and Ca saturation of the CEC. They also have a large content of organic matter and considerable biological activity. Soil pH varies greatly due to the nature of the deposited material. At the transition of these areas to neighbouring desert, the soils are more sandy or calcareous and of lower fertility.

5.3. Constraints and recommendations

5.3.1. Drought

In arid climates, drought during long periods, together with high temperatures and evapotranspiration, is one of the major constraints to plant growth. The small volume of soil solution has a high osmotic pressure that limits the uptake of water and the transport of nutrients by mass flow and diffusion to the root surface. This movement of water and nutrients is further hampered and aggravated by the high soil pH and bicarbonate content. Plants react by decreasing transpiration by closing stomata, absissic acid (ABA) activation and proline production. Decreasing cell turgor inhibits important physiological reactions/activities like protein and carbohydrate metabolism, and this finally stops growth and biomass production. Drought periods are especially harmful during seed germination and emergence. Harvesting and conservation of the small and irregular amounts of rainwater are necessary, either in tanks or natural cavities covered with plastic sheets, to conserve water for the needs of humans, animals and growing vegetables and fruit trees by subsistence farmers.

Drought tolerant cultivars develop a voluminous, finely branched root system, increasing the root/shoot ratio, which allows them to exploit a larger soil volume for water and nutrients. The adverse effects of drought can be partially minimized through adequate K fertilization. Plants well supplied with K can tolerate water stress more efficiently through closing the stomata, and can thus recover from partial wilting. The K content of leaves should be not less than 1.5 % in dry matter. The K can be applied to the soil or more effectively by foliar application with NOP or SOP, both of which are quickly incorporated into the leaves.

5.3.2. Wind erosion

Wind erosion can be disastrous in arid conditions removing the surface soil with the inorganic and organic compounds that contribute to soil fertility. With the high temperatures, the bare soil skeleton becomes compacted and crusted, preventing infiltration of the sporadic rainwater. Thus, water runoff and soil erosion is dramatically increased by heavy rain and this results eventually in desertification. The impact of erosion is greater where excessive grazing destroys the grass covering the soil. Maintaining a mulch at the soil surface improves water infiltration and helps minimize loss of soil by wind erosion.

In cultivating these soils, minimum or zero tillage should be practised together with direct seeding and maintaining a surface mulch of organic material. In the larger areas of agricultural production, wind breaks have to be established with trees, such as *Casuarina equisetifolia*, a non-leguminous N_2-fixing tree, or shrubs such as pigeon pea depending on water and nutrient availability, especially during early growth. Small grains for human food and animal feed, such as chickpea or cowpea can be grown.

5.3.3. Nitrogen deficency

Nitrogen deficiency is a major nutrient constraint in all types of arid desert soils due to the very low content of organic matter and very little use of legumes. The application of all kinds of organic manure and residues, the acquisition of atmospheric N through legumes and adequate mineral fertilization in an integrated nutrient management programme improve both plant growth and soil fertility. Nitrogen fertilizers should be applied in small doses and band or side-dressed just before rain is expected. The amount of fertilizer applied can be adjusted according to expected precipitation and the soil type. For example, the larger yield potential of the alluvial Fluvisols allows the use of more fertilizer.

5.3.4. Phosphorus deficiency

Phosphorus deficiency limits yield, especially on sandy soils with high pH and $CaCO_3$ content. The small amount of P is either adsorbed on $CaCO_3$ or chemically fixed in hydroxyl-, carbonate- and fluor-apatites, which are

insoluble under neutral and alkaline conditions. Alluvial and Rendzina soils contain more total P, and more is held in plant available forms on soil organic matter. However, they also need larger amounts of P fertilizers to achieve optimum yields. Soluble P fertilizers such as SSP and TSP are converted rapidly into di- and octo-calcium phosphates, which lessens their immediate availability to plants.

All P fertilizers should be placed in bands near to the roots to ensure that excreted protons and chelating substances minimize P reactions with soil constituents (Figure 2, page 8). The small water content of the soil and a low transpiration rate of plants with small root systems, hamper the transport of phosphate ions by mass flow and diffusion in the soil. In soils with a high pH, legumes have great importance through their acidifying effect, which can decrease pH by 2 units in the rhizosphere, thus increasing the solubilization of phosphates.

5.3.5. Potassium and magnesium

Generally, most Acridisols have large reserves of basic cations due to pedogenesis and absence of chemical weathering and leaching. In consequence, with subsistence farming, deficiencies of these nutrients are not so frequent. In the Mediterranean area, calcareous soils with a pH between 7.0 and 8.3 are widespread. If low in salinity and exchangeable Na they can be profitably farmed with (drip) irrigation, fertilization and foliar application of micronutrients. However, in soils with calcic or gypsic sub-horizons, most of the cation exchange sites are saturated with Ca or Mg. This, together with the inherently poor K status of these soils, makes regular large applications of K fertilizer necessary to achieve optimum growth. When irrigated and intensively cultivated, crops grown on these soils appear to be severely K deficient, especially those with a large K requirement, like vegetables, fruit trees, legumes, oil crops and cotton. The same is true for flooded alluvial soils, cropped twice or three times per year. Under saline conditions SOP is preferred to MOP. Potassium nitrate has also proved to be a suitable source of K, especially for crops grown under glass and plastic houses. Rootstocks of fruit trees and varieties of crops should be selected for their ability to acquire K under moisture and alkaline stress. In Egypt, the loss of the fertile Nile mud, rich in the mineral illite, below the High Dam at Aswan, means that the soils now need regular applications of K fertilizers. Experiments in the Negev desert in Israel have shown that drip irrigated tomatoes and melons not only tolerate slightly saline irrigation water but also have better quality when supplied with K.

5.4. Land use and farming systems

5.4.1. Dryland farming

Dryland farming under arid or extremely arid conditions has very limited possibilities. Grazing without or with improved pasture or alfalfa cropping is practised when winter precipitation is 200-300 mm on the Mediterranean or Atlantic coast of Africa. Spring wheat can be successful in a flexible rotation system together with other small grains or forage legumes, depending on the availability of moisture. Drought tolerant and deep rooting cultivars are superior. Fruit trees, such as apples and pears, as well as grapes and vegetables can give good yields in coastal areas or in oases with large fertilizer inputs. Hot and dry winds that desiccate the plants are a major constraint while frost can be very harmful to fruit trees. There can also be a problem from lack of chilling temperatures in winter that can prejudice uniform re-growth in spring.

5.4.2. Irrigation

Irrigation plays the key role in arid regions and is discussed in more detail in Chapter 2.6. The economic and agricultural advantages often outweigh any possible disadvantages provided the necessary follow-up measures are enforced and the water is properly managed. Irrigation offers great possibilities for growing many tropical crops, such as rice, cotton and sugar cane, to ensure adequate food supplies for the increasing population in many developing countries.

To achieve the large yields that are possible with irrigated crops requires increased fertilizer use based on nutrient input/output balances. However, misuse of water and improper or excessive fertilizer use creates great harm to the environment and can lead to soil degradation as shown by examples from various regions of the world. Salinity is the major hazard when using irrigation and it can lead to desertification and loss of fertile land.

5.5. Summary

The main climatic constraints of the arid tropics are drought and wind erosion. Conserving soil moisture, through appropriate soil cultivation techniques, and having windbreaks are important.

The main nutritional problems of these soils with a high pH and a large carbonate content are the small total N reserves, the very limited availability of P and micronutrients, and the imbalance of K, which needs site-specific inputs.

Dryland farming is very restricted. With irrigation, yields can be increased considerably. Optimal irrigation management, such as drip-irrigation and fertigation, a functioning drainage system and water saving methods are necessary to avoid salinity, which can lead to total desertification. Cultivars tolerant to drought and salinity should be grown.

6. Rice cropping and rice soils

In many countries in the tropics and subtropics, rice is the most important food crop. It can be grown in a wide range of climatic and soil conditions and in monoculture or in crop rotations (Greenland, 1997).

6.1. Soils and cropping systems

Upland rice is grown predominantly in Africa and South America but yields are often less than those of irrigated rice grown in other parts of the world. The nutrient requirement, fertilization problems and cultivation practices are similar to those of other cereals grown under rainfed conditions.

Irrigated paddy rice covers about 60% of total rice area. Irrigated paddy rice soils are often originally Vertisols but the crop is grown on Entisols, Mollisols and Alfisols, which have been changed completely anthropogenically due to permanent rice cropping. The fields, surrounded by low mud borders, are ploughed when the soil is saturated with water and puddled to break down soil aggregates and get uniform mud (Plate 13). Rice seedlings, grown for 15-30 days in a nursery bed, are transplanted on to the paddy fields. Because this is labour intensive, this system is mainly practised in countries with a low labour cost. Where topography is suitable and labour cost high, mechanized direct seeding is used, for example in Egypt and Japan. Weed infestations are a problem with direct seeding so that the application of herbicides is necessary.

Alternate anaerobic and aerobic conditions due to flooding and drying affects the redox-potential, pH and the availability of nutrients (Figure 10). Initially, in the flooded upper few centimeters of soil, conditions are aerobic because the floodwater still contains dissolved oxygen. In contrast, the deeper grey-blue or black soil layers are anaerobic with a negative redox potential depending on the amount of decomposable organic matter. As a consequence, first NO_3 is denitrified to dinitrogen gas (N_2) or nitrous oxide (N_2O), which escape to the air. Then Mn compounds are reduced to Mn and $Fe(OH)_3$ to Fe. This process leads to a release of OH^- ions and can cause Fe or Mn toxicity, depending on the level of organic matter and temperature. The reduction process removes H^+ ions and, in the flooded layers, the pH increases to about 7, with a favourable increase in the availability of P and other nutrients. When the soil dries, all these reactions are reversed. The rhizosphere of rice plants is aerobic due to a specific internal air transport system (aerenchyma) and the release of oxygen (O_2) from young active roots.

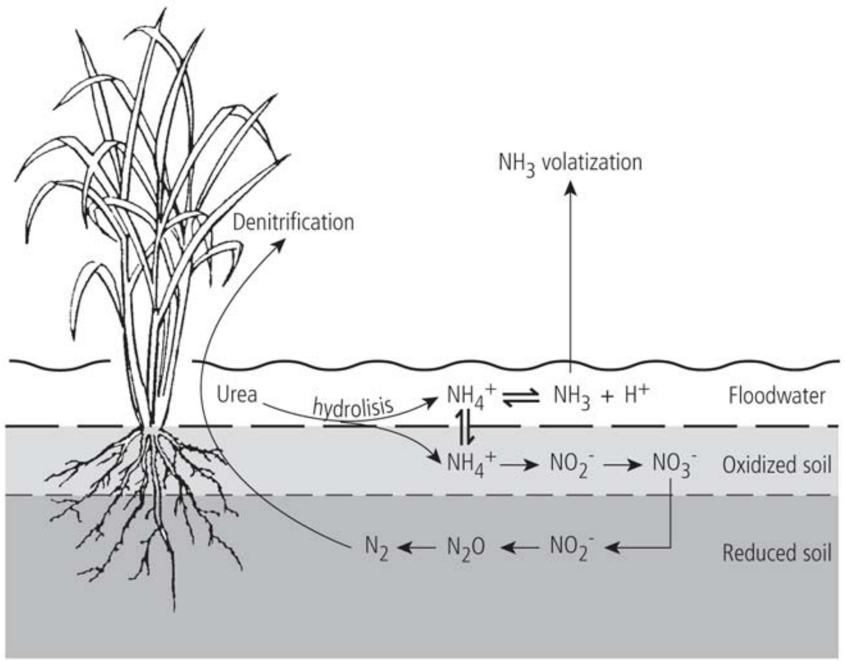

Figure 10. Nitrogen dynamics in soils growing rice (Adapted from Vlek and Fillery, 1984)

6.2. Nutrient management

Rice has a large requirement for water and nutrients, especially K and N. Urea is the most frequently used N fertilizer and losses of more than 50% of the N can occur mainly through NH_3 volatilization, less through denitrification. These losses are of concern both for economic and environmental reasons. The greatest losses of NH_3 occur when urea is broadcast into the flooded upper layer with neutral pH due to the rapid conversion of urea to NH_3 and CO_2 by urease in the soil. This results in a further rise in the pH of the floodwater. An NH_4-containing or producing fertilizer is preferred and is either incorporated into the soil before seeding or broadcast into the anaerobic soil layer to prevent rapid oxidation to NO_3 with subsequent losses through leaching or denitrification. Incorporating straw and green manure reduces N_2O emissions. Supergranules and S-coated urea can be placed deeper by hand to avoid losses of NH_3 by volatilization. The timing and splitting of N fertilizer applications has to take account of the large N requirement at tillering and at panicle initiation. The addition of a urease inhibitor, like phosphorodi- or tri-amidate, or a nitrification inhibitor to the N fertilizer before application can help reduce N losses.

Where soils are not acid and contain sufficient available P, the tropical floating tiny water fern *Azolla pinnata* grows rapidly in the water where paddy rice is grown in association with the N-autotrophic bluegreen algae *Anabaena*. Through this symbiosis, considerable amounts of atmospheric N (60-100 kg/ha) are fixed. Rice plants can use this symbiotically fixed N and this decreases their requirement for fertilizer N. Intercropping of *Azolla* and rice also mitigates NH_3 volatilization, decreasing the flood water pH by about 2 units. Thus, the recovery of urea-N by rice can be significantly increased (Cisse, 2001).

All types of P fertilizers, including low grade PRs, are suitable for growing rice. Silica also is an essential element for rice, increasing its resistance to pathogenic fungi. Rice, especially the high yielding varieties, need large amounts of K. Lack of K causes stunted plants with dark green leaves and short thin stems. Later in growth, brownish spots spread over the whole leaves and the grains are sterile. Adding K reduces Fe toxicity. It is a matter of concern that in many rice growing areas there is a negative K balance.

Though the required amount of Zn is not greater than 1 kg/ha, Zn deficiency is the most serious micronutrient deficiency in rice soils due to the high pH in the surface soil. It can be controlled by applying zinc sulphate, chloride or nitrate to the soil or through foliar application of the sulphate or chelated Zn (e.g. Zn-EDTA). There are marked differences between cultivars in relation to Zn deficiency and tolerance to lack of Zn.

The great importance of rice to the food security of so many people, especially in developing countries, has led to a great deal of research in recent years. In part, this was driven by stagnating yields in many places and some reports of declining yields. Results from China (Wang *et al.*, 2001) and Bangladesh (Alam *et al.*, 2005) have been reported recently. A site-specific nutrient management approach (SSNM) has been evaluated at numerous locations in Asia (Wang *et al.*, 2001; Dobermann *et al.*, 2002 and Dobermann *et al.*, 2003). Field-specific, balanced amounts of N, P and K were prescribed for each site. These were based on crop estimates of the soil's indigenous supply of N, P and K (determined by the omission plot technique) and by modelling the expected yield response as a function of nutrient interactions and climatic yield potential (Dobermann *et al.*, 2002). In addition, the timing and amount of N applications were fine-tuned to crop needs based on leaf chlorophyll content (Peng *et al.*, 1996) measured at critical growth stages of rice. Estimates of leaf chlorophyll content are based on the use of leaf colour charts (LCC) that indicate how green the leaf should be at different growth stages. Leaf colour below or above the "ideal" colour indicates the need to apply N or withhold an application. Such colour charts are readily available. Undertaking a series of omission plots is more onerous. These current nutrient management concepts are knowledge intensive and it will now be necessary to see if they can be simplified for wider scale adoption without loosing precision and potential gains in yields, profitability and nutrient efficiency.

The Swiss Agency for Development and Cooperation (SDC), together with IFA, IPI and PPI/PPIC, has co-sponsored this "Reaching Towards Optimal Productivity" (RTOP) multinational project to develop and disseminate SSNM for irrigated rice in Asia. The project has been executed by the International Rice Research Institute (IRRI) together with the National Agricultural Research and Extension Systems (NARES) in each of the six countries that were members of the consortium. The results have confirmed the importance of using the leaf colour charts to decide the need for fertilizer N. In some cases this has led to not applying a basal N dressing before planting and applying split applications of both N and K to meet changing demands during growth. Omission plots have indicated the need for P and K and micronutrients and the indigenous soil supply. The importance of following the principles of balanced fertilization has been clearly demonstrated. The next phase of this important project will be to disseminate and encourage the uptake of the principles of SSNM.

7. Salinity

Growth can be inhibited by a high osmotic pressure in the soil solution due to the total salt concentration, greater electrical conductivity of the soil solution and more negative water potential lowering turgor in the plant cells. The high osmotic pressure of saline water inhibits the uptake of water and nutrients by the roots, mainly those nutrients such as K, P and micronutrients that are transported by mass flow in the soil solution. Growth can also be impaired by toxic concentrations of Na and Cl ions or by an ion imbalance, for example the ratio of Na:K; Na:Mg. The typical symptoms of salt and/or Na toxicity are plants with stunted roots, destroyed cell membranes, blue-green colour of the leaves with marginal chlorosis and necrosis symptoms. With legumes, salinity decreases symbiotic N fixation.

Sodium toxicity mainly occurs with grasses, wheat, sorghum, rice, while Cl toxicity appears on citrus, avocado, legumes and herbaceous species. Many plants can tolerate higher concentrations of Cl than of Na. A high Na concentration in the soil solution injures plants directly by inhibiting the uptake of K, Ca and Mg and displacing Ca ions from the plasma membrane of roots (Amberger, 1998). Through interacting with K-dependant enzymes, protein and carbohydrate synthesis is impaired and, finally, Na induces K or Mg deficiency (Shaviv and Hagin, 1993). In an experiment with grape vine, a crop moderately tolerant to salinity, increasing amounts of NaCl, from 2 to 150 meq/l, caused a dramatic decrease in K, Ca and Mg in the roots and leaves and severe chlorosis and necrosis symptoms on mature leaves (Table 11).

Under normal conditions, the cytosol of higher plants contains 100-200 millimole (mM) K and only 1 mM Na, and Na does not replace K in its physiological functions in the plant. Potassium is the most important inorganic solute in plants. Consequently, K supply is very important under

Table 11. Effect of salinity on the nutrient content of grapevine roots and leaves (Adapted from El Fouly and Salama, 1999)

NaCl	Na	K	Ca	Mg
meq/l		Roots (% in dry matter)		
0	0.10	1.85	2.36	0.26
10	0.16	1.24	1.69	0.23
40	1.67	0.96	0.47	0.20
150	4.99	0.43	0.34	0.06
		Leaves (% in dry matter)		
0	0.08	1.74	1.28	0.21
10	0.17	1.21	1.19	0.12
40	0.70	0.98	1.27	0.10
150	3.62	0.78	0.49	0.09

saline conditions and K competes efficiently with Na in their uptake by roots. Thus, applying adequate amounts of K can mitigate or even prevent Na uptake. In this role, SOP is preferred because of possible adverse effects of Cl added with MOP. Also, foliar applications of NOP can increase plant tolerance to salinity. Citrus rootstocks show marked differences in the beneficial effect of K on salt toxicity.

Some plants can limit their uptake of salt (salt excluders) due to the presence of lipid compounds in the root cell membrane. Other plants transport Na to the shoots (salt includers), where Na is sequestered in the vacuole or is secreted through specific salt-glands in the leaves from which the Na is leached by irrigation water or rain. The salt-tolerant *Chenopodiaceae* (e.g. spinach) uses Na ions for turgor maintenance, *Gramineae* produce organic solutes such as betain or proline to lower the osmotic potential. Bernstein (1970) gave an extensive list of the level of EC at which yield is decreased by 25%. A selection of crops is indicated in Table 12. In general, sugar beet, barley, tomato, melon and cotton plants and date palms show the greatest salt tolerance. Of medium tolerance are sorghum, millet, wheat and maize. Legumes (e.g. bean), carrots, pepper, onion, sugarcane, citrus, avocado and other fruit trees are very sensitive to salinity. However, there are great differences between forage crop cultivars and between rootstocks of fruit trees

Table 12. Level of electrical conductivity (EC) at which yield is decreased by 25% (Adapted from Bernstein, 1970)

	EC (dS/m)		EC (dS/m)
Barley	15.8	Rice (paddy)	6.2
Sugar beet	13.0	Maize	6.2
Cotton	12.0	Sesbania	5.8
Safflower	11.3	Broad bean *(Vicia)*	5.0
Wheat	10.0	Flax	4.8
Sorghum	9.0	Beans *(Phaseolus)*	2.5
Soybean	7.2		

in their tolerance to salinity. Differences in salt tolerance are due to physiological mechanisms. Contradictory statements concerning susceptibility to salinity are found when soil properties, like sand, clay, organic matter content, are not considered.

Screening shows great potential for the selection of cultivars adapted to saline water. Also modern gene techniques could be helpful in introducing salt tolerance traits from wild relatives of cultivated plants. In soybean, for example, a single gene pair is responsible for the exclusion of Cl.

Salinity is the major hazard when using irrigation and it can lead to desertification and loss of fertile land (Plate 14). Soluble salts added with irrigation water can remain on the soil surface or be brought back to the soil surface as the applied water evaporates. The larger the amount of water applied, the larger the wetted zone in the soil in which soluble salts are mobilized and, as a result, the risk of added salinity increases as the water table rises. Water-saving irrigation methods will minimize or even prevent the development of salinity.

To make irrigation successful and overcome salinity problems where irrigation is practised, requires observance of some general rules.

Irrigation water quality is important and is classified in terms of electrical conductivity (EC, expressed as deci Siemens per meter (dS/m) soil, and determined in the 100% wet soil paste) and in terms of total salt concentration (g/l water). These two parameters are closely related. The US Salinity

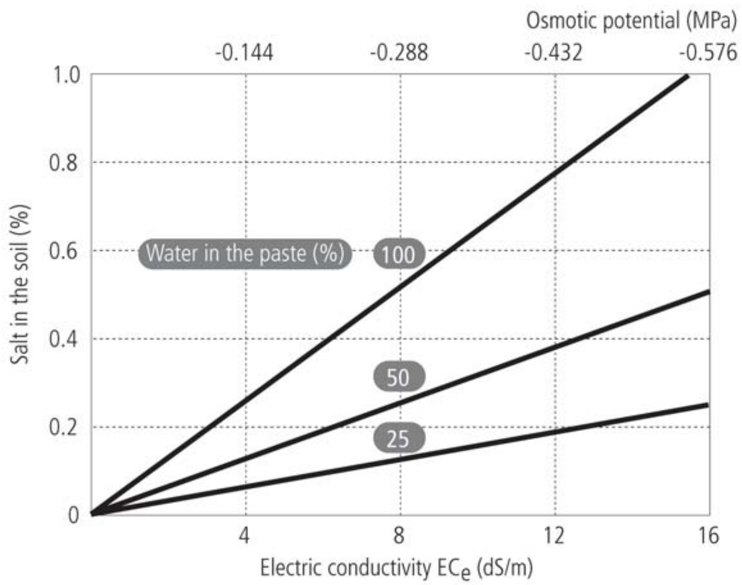

Figure 11. Relation between percent salt in soil and its electrical conductivity and osmotic potential (Adapted from Richards, 1954)

Laboratory gives some general rules for using irrigation water effectively. The EC should not exceed 0.75 dS/m, equivalent to about 0.5 g salt/l (0.05%). Salinity problems are likely to occur if the EC of the water exceeds 1.5-3.0 dS/m. Using water with a higher salt content for irrigation must be controlled carefully. However, brackish water and municipal wastewater can be used successfully on more salt-tolerant crops, like tomatoes and melons, or when mixed with better quality water. Figure 11 shows the interrelationship between EC, osmotic potential and salt content of soil.

Sodium content is an important indicator for irrigation water quality. It is expressed in terms of the sodium adsorption ratio (SAR) in relation to the concentration of Ca and Mg ions:

$$\text{SAR (meq/l)} = \frac{Na^+}{(Ca^{2+} + Mg^{2+})/2}$$

SAR values >9 cause problems of water penetration into the soil. A high concentration of exchangeable Na results in peptization of soil colloids and destruction of soil structure. The increased uptake of Na by plants leads to problems of cation imbalance and the inhibition of certain enzymes involved in metabolic processes.

Bicarbonate concentration. A large concentration of bicarbonate (HCO_3^-) in the irrigation water can also be harmful. The quantity is expressed as the residual sodium carbonate (RSC) concentration:

$$\text{RSC (meq/l)} = (CO_3^{2-} + HCO_3^-) - (Ca^{2+} + Mg^{2+})$$

Water with RSC values of 1.25-2.5 is marginally suitable for irrigation.

Other elements. Among the toxic elements, boron (B) (as Na borate) must be controlled in municipal wastewater because a concentration of 1.5 mg/l may injure B sensitive crops like fruit trees.

Irrigation management aims to maximize water use efficiency and prevent the development of salinity. Among the factors to be considered are the rate of water infiltration into the soil, the timing and calculation of water need, the crop's irrigation coefficient factor and the nutrient requirement of each crop. Modern water saving methods that use minimum amounts of water and restrict the volume of the wetted zone, maintain a less saline environment in the root zone while creating a highly saline zone at the border of the wetted zone. Excessive irrigation, together with a lack of an appropriate drainage system, is the main cause of salinity as demonstrated by examples from Egypt and the Near East. A functioning drainage system has to be planned as part of an irrigation system from its installation so that periodically (perhaps every 4-6 years, depending on soil texture and structure) the accumulated salts can be leached from the surface soil with 200-500 mm water. Lake Karoun in the Fayoum oasis in Egypt is a good example; the drainage water is led into the salt lake at the deepest point of the oasis. When considering the amelioration or reclamation of soils affected by salinity, it is essential to first determine which is the real hazard: salinity, alkalinity or bicarbonate concentration.

Irrigated soils are roughly classified as follows.

Saline soils have an EC>4 dS/m soil and <15% exchangeable Na. The cations are mainly Na, Ca and Mg, the anions are mainly Cl and SO_4. Accumulated salts can be easily leached out and this is the only method of amelioration. Examples are alluvial soils derived from sandstone and shales with pH<8.2 where water infiltration is rapid. After leaching, large applications of K are required.

Alkaline or sodic soils have an EC<4 dS/m soil, >15% exchangeable Na and a pH>8.5. The anions are mainly Cl, SO_4 and HCO_3. These soils are impervious to water and air, and root penetration is impeded because the soil aggregates have been destroyed. The high Na concentration and deteriorating soil physical properties induce K deficiency and this limits growth. These soils can be reclaimed by applying soluble Ca salts, e.g. gypsum, to replace the excess Na ions on the CEC. Gypsum works best in soils with a low salt but high bicarbonate content.

Saline-Alkaline soils have an EC>4 dS/m soil, >15% exchangeable Na and a pH of 6-8. Such soils are widespread, mainly alluvial soils derived from silicates and other parent material. Reclamation often requires deep ploughing or ripping to 75 cm depth to break up soil pans or hard layers that inhibit drainage. Covering the soil with plastic sheets, application of green manure and mulching with organic material reduces evaporation and favours water infiltration. Excess Na on the CEC must be replaced by Ca and be followed by adequate applications of K.

Calcareous soils, with EC<4 dS/m soil and <10% exchangeable Na, are rich in calcium carbonate and therefore non-saline. The main constraints here are an imbalance of cations and the extremely low content of available K. Usually, calcareous soils do not pose severe management problems but they do require large applications of K.

Saline-Alkaline and Calcareous soils can be amended by applying SO_4 ions, which when leached from soil will take Na ions as an accompanying cation. Sulphate ions are produced by applying sulphuric acid or pyrite (FeS_2), ferrous sulphate or elemental S. These soils can also be amended by adding acid-forming fertilizers to lower soil pH and increase the availability of P and micronutrients. Ammonium sulphate, ammonium thiosulphate or iron sulphate also have a pronounced effect in lowering the pH. For soils with only little salt and a relatively large bicarbonate content, the application of gypsum is a common practice.

The reclamation of highly salt-affected soils is very difficult, costly and should be done early enough to counteract and avoid any over-salinization. However, no plant will grow on a completely salted, alkaline soil, and such soils must be abandoned.

8. Micronutrients

Although required in only small amounts, a number of micronutrients are essential for the growth and well-being of animals and plants. Vlek (1985) gave a general review of the role of micronutrients in tropical food production. Where the soil supply is deficient in those elements that are essential, their application has considerable potential to increase food production. Micronutrient requirement increases as the application of macronutrients increases, especially where high yielding varieties are grown. Fruit trees, vegetables, oil palm and, to a lesser extent, legumes, cotton and root crops are very susceptible to micronutrient deficiencies. There are striking differences between crop genotypes in the efficiency with which they acquire micronutrients from the soil. Genotypes probably differ in rhizosphere acidification, type of root exudates and their reducing capacity, and variations in mycorrhizal associations, which particularly improve the uptake of Zn and copper (Cu). This potential for genetic adaption of plants to adverse soil conditions could be exploited to decrease, at least partly, the cost of micronutrient applications.

8.1. Soils and cropping systems

The total content of a micronutrient in soil and its availability both vary greatly depending on parent material, soil type and climate. In general, coarse textured soils are poor in micronutrients, whereas fine textured soils may be relatively rich. The total natural content of micronutrients in the highly weathered, oxidized soils in the humid tropics is very small due to soil erosion and the leaching of easily soluble, mobile forms. Although Fe and Mn oxides may be present in large amounts, they are insoluble. Highly weathered soils are also mostly depleted in Mo and B, and low in Zn, Mn and Cu. It is essential to ensure that high yielding, intensively managed crops, such as coffee, coconut, banana, oil palm, all kinds of fruit trees, vegetables and root crops, do not suffer from micronutrient deficiencies. Legumes have a specific requirement for Mo and deficiency is a common problem on acid soils due to adsorption of molybdate on sesquioxide surfaces. Molybdenum deficiency sometimes occurs in combination with a deficiency of Mn and Cu.

The relationship between the total and soluble/plant available micronutrients is complex. The latter depends on soil pH, redox potential, amount of SOM, clay content and CEC and biological activity. In general, solubility increases as pH decreases and, in acid soils, concentrations can in some cases reach toxic levels, for example, with Mn and Fe, which at high pH are precipitated as insoluble oxides. Heavy metal ions can change their charge if the redox potential of the soil changes. At high pH and under oxidizing conditions, Fe^{II} changes to Fe^{III} and Mn^{II} to Mn^{IV} and, in consequence, they can become deficient. At low redox potential, under anaerobic conditions, the divalent forms of these metals predominate. For example, under irrigation, there is a low redox potential when the soil is flooded and micronutrients become available to plants, occasionally in such large amounts that they can become toxic. However, in the following aerobic period, the situation is reversed. Oxygen consumption due to the respiration of roots and microorganisms can decrease the redox potential in the rhizosphere and therefore affect micronutrient availability. Drought intensifies micronutrient deficiencies because micronutrients are transported by mass flow in the soil water. If a practice could be identified that would increase the availability of naturally occurring micronutrients in soil, it would be of great benefit to small-scale subsistence farmers.

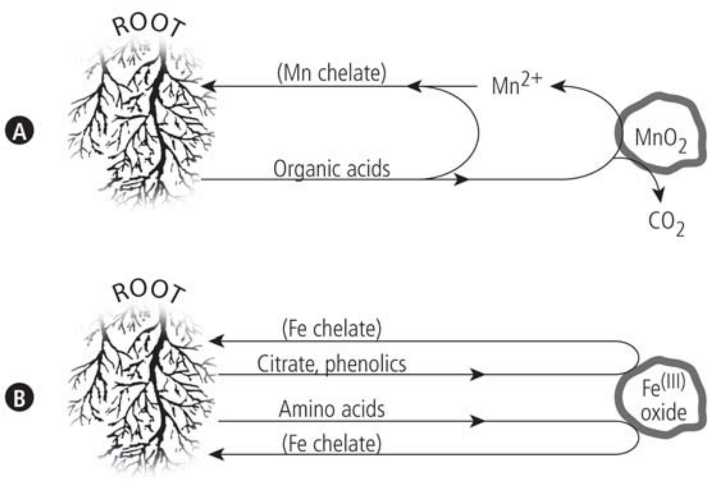

Figure 12. Schematic representation of possible mechanisms for the solubilization of sparingly soluble inorganic compounds by root exudates in the rhizosphere (Adapted from Marschner, 1986)

Biological activity and the activity of plant roots are important in solubilizing micronutrients in soil (El Gala and Amberger, 1988). Possible mechanisms involved are illustrated in Figure 12. Organic matter, like plant residues and farmyard manure, usually improve the availability of soil-borne micronutrients through delivering protons and supplying reducing and chelating substances during their decomposition. These substances lower soil pH and form complexes with micronutrients, which thus become available to plants.

The solubility of micronutrients in the rhizosphere, which is rich in organic acids, phenolics and hydroxamate siderophores (iron transporters), differs in many respects from that in the bulk soil. Rhizosphere acidification by many dicotyledons increases micronutrient uptake, for example of Zn and Fe. This mechanism is strictly limited to the rhizosphere, that very small zone of soil about 5mm around the root. Thus, a large and dense root system with its associated rhizosphere helps a plant to explore a greater volume of soil. Acidifying fertilizers also increase the availability of micronutrients by decreasing soil pH in the rhizosphere (Figure 13 and Table 13).

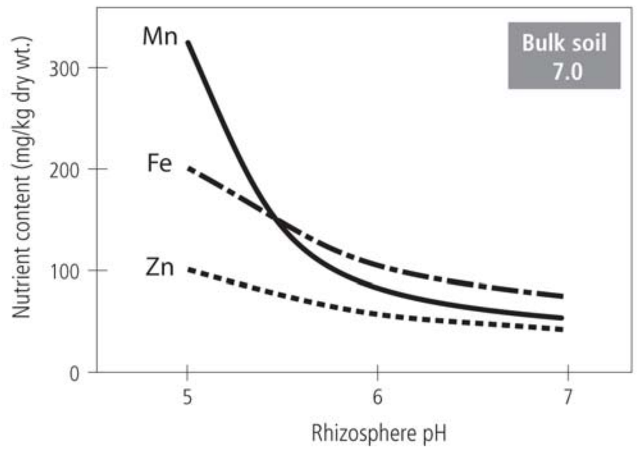

Figure 13. Effect of rhizosphere pH on the content of manganese (Mn), iron (Fe) and zinc (Fe) in the shoot of bean plants (Adapted from Römheld, 1993)

Table 13. **Effect of the type of nitrogen fertilizer on micronutrient uptake per meter length of bean root *(Phaseolus vulgaris)* (Adapted from Marschner and Römheld, 1996)**

Fertilizer	Uptake (µg per m root length)			
	Fe	Mn	Zn	Cu
Calcium nitrate	68	23	11	2.7
Ammonium sulfate (+ nitrification inhibitor)	184	37	21	3.7

8.2. Micronutrient deficiencies

Sillanpäa (1982) concluded from an investigation on micronutrients that Zn deficiency is the major micronutrient that constrains yield in many soils in Africa, the Near East and Middle East and the Mediterranean countries, as well as in the Brazilian Cerrados and Colombian Llanos. Zinc is often deficient in alkaline soils, with very obvious symptoms especially on fruit trees (bare branches and little leaf rosettes on top) and legumes (Plate 15) but also in wetland rice. At high soil pH, Zn ions are strongly adsorbed on clay and carbonate particles but desorption can be increased significantly by organic acids. Crop yields can be increased by applying soluble Zn salts like $ZnSO_4$ or less soluble compounds like ZnO and $ZnCO_3$ to the soil in large amounts. The availability of added Zn declines relatively quickly as insoluble compounds are formed. Mycorrhizal associations can aid the uptake of Zn by the host plant. Zinc deficiency occurs on high-yielding varieties in India, and was found to be a limiting factor for wheat production in Turkey (Cakmak *et al.*, 1996). However, Zn deficiency could be corrected by adding Zn to compound fertilizers and this method has contributed an economic benefit of some US$ 100 million in Turkey (Cakmak, 2004).

Iron chlorosis is associated with yellow young leaves on all kinds of fruit trees, grapevines and legumes (Plate 16) (Römheld and Marschner, 1984). Deficiency is greatly increased when the soil solution contains much bicarbonate, which induces lime chlorosis, and by increased bicarbonate excretion from the roots in the presence of NO_3. Lime-induced chlorosis is often correlated with large amounts of total Fe in the soil. Cultivars of maize, sorghum and other cereals differ in their susceptibility to Fe chlorosis (Romheld, 1993), hence screening for Fe-efficient cultivars is a major tool for counteracting the problem.

Manganese deficiency occurs mostly in well-aerated alkaline and calcareous soils where Mn is present as MnO_2 or adsorbed on $CaCO_3$. But deficiency is also found in intensively cropped alluvial soils. Correction of this problem can be achieved through soil or leaf application of $MnSO_4$.

Copper deficiency in soils in arid climates is restricted mainly to sandy desert soils. The requirements of crops are very small and can be corrected through foliar application of $CuSO_4$ or Cu chelates. Root colonization with arbuscular mycorrhizae may markedly increase the Cu and Zn content in plants.

Molybdenum is the only micronutrient that is more available to plants at high soil pH. However, the natural supply in arid soils is very small and often limits growth, especially of legumes, which require it for nodulation.

Boron is usually present as boric acid in the soil solution and behaves like a non-metal (such as silicon). Deficiency can occur, especially at high pH, due to the strong adsorption of borate on clay minerals in the pH range 7-8. When municipal water is used for irrigation, B toxicity is often a problem. In sub-Saharan Ferralsols and Fluvisols and also in Mediterranean Rendzinas, the amount of B is small due to the high pH of the soil and adsorption of B on Fe oxides. Boron is of particular importance for oil palm in West Africa.

8.3. Managing micronutrients

Deficiencies of micronutrients can be controlled to some extent by optimal water management, application of organic matter, improved soil microbial activity and application of acidifying N fertilizers. Incorporation of soil-applied, commercially available inorganic compounds, even of low solubility, such as oxides, carbonates, silicates and molybdates, can help overcome deficiency but such compounds have to be available locally. Application of inorganic micronutrient salts near the roots is better than broadcast applications. The same is true for synthetic chelates like ethylene diamine tetracetic acid (EDTA), N-(2-hydroxyethyl) ethylenediaminetriaceticacid (HEDTA), diethylene triamine pentaacetic acid (DTPA) applied to soil, but the costs are much greater. The application of soluble inorganic salts or, still better, of chelates as a foliar spray allows much smaller amounts to be applied and guarantees a rapid response. The uniform distribution on plant leaves allows uptake often within hours or, at most, within some days. Following incorporation into the plant, an immediate obvious response is visible. These properties of foliar applied chelates and their advantages allow the correction of deficiencies even when the symptoms are noticed late in the growing season. However, too high a concentration or application in direct sunshine can lead to leaf scorch. The greater price of chelates can be prohibitive for small-scale farmers. Coating seeds with micronutrient compounds or dipping roots into micronutrient solutions can supply micronutrient requirements during germination and early growth.

Soil testing, for example by extraction with DTPA or, better, plant analysis can both be used to assess the micronutrient status of crops and soils. If visual symptoms suggest a micronutrient deficiency, it can be confirmed by analysis. However, data have to be calibrated with the critical levels available in the literature for each crop.

When planning a micronutrient strategy, the great genetic diversity between plants in their ability to absorb micronutrients could be used to great benefit. A large number of fruit tree rootstocks and vegetable cultivars are strickingly efficient at micronutrient uptake. For example, citrus rootstocks from bitter lemon are less susceptible to Fe chlorosis compared to other strains. Developing and using such cultivars would be a much better solution than repeated costly foliar sprays. There should be intensive screening among cultivars to find out which are tolerant of micronutrient deficiencies or, alternatively, identify cultivars that are efficient at mobilizing and utilizing micronutrients already present in soil by active proton efflux, which decreases pH, and/or excretion of reducing and chelating substances that react with micronutrients and improve their uptake.

8.4. A case study evaluating micronutrients

An excellent example of the importance of recognizing micronutrient problems and seeking solutions comes from a joint Egyptian - German project (El-Fouly and Abdalla, 1996). It was initiated as pilot project and was carried out in Egypt at the National Research Center (NRC), Cairo. In 2006, it is still running autonomously by the Egyptians, scientifically assisted by different German institutions.

Initially, the issues centred round the fact that crop yields were declining on alluvial soils in the Nile valley that had been cultivated for many years. Possible reasons included growing two or more crops each year, including wheat, clover, faba bean in the cooler winter months and maize, rice, cotton,

sugarcane in the hotter summer months. Also, cultivars with a large yield potential and, therefore, a large requirement for nutrients, had been introduced. Emphasis had also been on applying N and P without adding K and other nutrients.

Micronutrient deficiencies, as well as a shortage of K and Mg, were found to be widespread in many Egyptian soils and in the arid areas from Morocco to Yemen, as well as in many other locations like East Africa, Pakistan, Iran and India. This gave greater relevance to this project on micronutrients because the methodologies, strategies and solutions that were developed could be applied throughout the region. Knowledge transfer and know-how would benefit many participants and would be very cost effective.

The project first developed specific fertilizer recommendations for the various field and horticultural crops that were grown as part of an integrated and balanced crop nutrition programme. The second phase was to ensure that the recommendations that were developed were passed to farmers to increase both yields and income.

The results of the project were:

i) Nutritional problems in major crops were identified, especially for wheat, maize, peanut, faba bean, citrus, grapes, mango, potatoes, tomatoes in 14 of the agricultural Governorates in Egypt and the newly reclaimed areas in the West Delta.

ii) Fifteen new micronutrient foliar fertilizers were developed to meet the specific needs of crops and soils based on a range of different materials including sulphates, chelated powders and chelated suspensions. This was done in cooperation with different companies.

iii) The most suitable ways of using micronutrient foliar fertilizers were developed to get the greatest efficiency under Egyptian climatic and agronomic conditions.

iv) A site-specific system was developed for calculating fertilizer recommendations at the farm level to achieve appropriate target crop yields. This system was based on soil testing, plant analysis and local agronomic practices. The system is now being adapted for use on a computer and is updated regularly as new information is obtained.

This newly developed system, including the use of micronutrients and the need for balanced fertilization, was first validated and then introduced to a greater number of farmers by establishing a “Revolving Fund”. This offered farmers the following services:

1) Soil testing and plant analysis
2) A survey of their farming system
3) Working out balanced fertilizer recommendations at the farm level
4) Providing micronutrient foliar fertilizers developed during the project according to need
5) Providing technical assistance about fertilizer use.

Although farmers had to pay for such services, they were highly subsidized initially, after which the farmer's contributions were gradually increased until they paid the actual cost.

To increase wider adoption of the system, the project gave advice to extension service staff and dealers on how to approach farmers about the need for micronutrients, and trained them on their proper use.

The project demonstrated that considerable increases in yield of major crops could be achieved in farmers’ fields by using micronutrient foliar fertilizers within the balanced nutrition concept. These increases ranged between 14 and 28 % (Table 14). In some cases, where a micronutrient was the major limiting nutrient, yield increases exceeding 100% were recorded, for example with peanuts on sandy soils.

These results encouraged farmers to join the Revolving Fund and benefit from its services. In 11 years, the Fund served about 70,000 farmers, either directly or through local agricultural cooperatives. The additional income to

Table 14. Average yield increases during 1985-1995 due to the use of micronutrients and balanced fertilization by farmers participating in the Revolving Fund activities.

Crop	%	Crop	%	Crop	%
Citrus	30	Cotton	20	Lentils	25
Mango	30	Wheat	18	Potato	20
Peaches	20	Rice	14	Tomato	15
Pears	20	Maize	24	Pepper	20
Apples	20	Soybean	24	Cucumber	20
Grapes	25	Peanuts	28	Protected vegetables	20

these farmers amounted to more than 48.8 million Egyptian pounds, an amount more than five times the total cost of the project. On average, nation wide, at least five times as many farmers are now using micronutrient fertilizers regularly in their fields compared to previously. However, due to a lack of appropriate fertilizers and technical assistance in some areas, the farmers there are unfortunately not getting the maximum possible yields but they are nevertheless increasing. Although these farmers probably get only about 50% of the benefits that farmers participating in the project get, their estimated additional income is about 100 million Egyptian pounds.

The importance of micronutrients as a yield-limiting factor in old and new lands is now no longer debated, and the official extension service literature includes recommendations to use micronutrients for at least 10 major crops. The Ministry of Agriculture recognizes the importance of soil testing, plant analysis and integrated balanced plant nutrition.

The project results encouraged fertilizer manufacturers to produce micronutrient foliar fertilizers tailored according to local needs and crops. To ensure the local availability of appropriate micronutrient foliar fertilizers, the German Government provided the NRC with a small-scale pilot plant for developing and producing these special fertilizers. The plant had at the same time, to demonstrate the possibility of using locally available raw materials for the production of micronutrient fertilizers. In setting up the plant, it was hoped to encourage investment in local production facilities and the Egyptian Government is giving such investment priority.

The project also demonstrated that unbalanced fertilizer use results in the excessive use of N fertilizers, leading to pollution of surface and underground water supplies. The use of balanced fertilization based on nutrient removal by harvested crops, soil testing and plant analysis, can optimize the efficient use of N and decrease hazards to the environment.

It was very clear that the project could not bring the concepts and the results to the majority of farmers without using the country's existing technology transfer methods. Therefore, a strategy for information dissemination to different target groups was developed. Extension service agents disseminated the results of the project through regular training sessions and provided farmers with information. Training was provided for teachers of agricultural chemistry and horticulture, and a curriculum for teaching plant nutrition was developed for use within the official curricula for the Ministry of Education.

9. Conclusions and outlook

The aim of this book is to focus on the main constraints on soil fertility and plant nutrition in the tropics and subtropics and present strategies and recommendations for fertilizer use and water management for sustainable crop production, while conserving soil resources.

In order of priority, by far the greatest and most crucial constraints to food production in this region are soil erosion, overgrazing, deforestation, soil nutrient mining and salinity. Each is a pathway that can lead to desertification and, therefore, to the loss of agricultural land. Each of these problems is man-made and is the result of local and regional mismanagement by farmers and communities.

These major constraints impair soil fertility and exacerbate the problems associated with plant nutrition, such as nutrient deficiencies and toxicities and the imbalance of nutrients. On the other hand, the fertility of agriculturally managed land can be maintained and even be improved through soil, water and fertilizer management appropriate to the site and the crop rotation practised. This includes growing legumes for their essential role of fixing atmospheric N, supplying organic matter and improving the nutrient dynamics within the soil.

Water management means harvesting and careful storage of rain, crop-specific irrigation with the most appropriate method of application, and drainage systems to remove excess salts. With irrigation, productivity can be greatly increased. However, the mismanagement of water, including its excess use and a lack of drainage system, leads to salinity problems and eventually to desertification.

Fertilizer management includes improving the efficiency of fertilizer use through crop- and site-specific application, minimizing losses such as volatilization, leaching and denitrification, decreasing erosion and utilizing organic wastes from plant and animal production. Nutrient inputs should be based on input/output calculations and the amounts adjusted according to the expected yield. Large inputs must be restricted to those sites and climatic conditions, where large yields can be expected, particularly in combination with irrigation. In this context, urease and nitrification inhibitors hold promise for improving N fertilizer use efficiency to benefit both farmers and protect the

environment. Intensive research of the soil-root interface in the rhizosphere and of mycorrhizal associations, as well as the identification of root properties are areas of promising research to improve nutrient use efficiency.

In the humid tropics/subtropics, Al toxicity and P deficiency are often major constraints, whereas in the arid tropics, high pH and soil carbonate content inhibit the availability of nearly all nutrients and favour the decrease of organic matter. Deficiencies of N, P, K and micronutrients due to the small amounts applied, unavailability and imbalance in the soil, pose great problems.

Apart from advanced techniques in soil cultivation, cropping, irrigation and fertilization, there is great biodiversity among crops and cultivars in their tolerance to stress. These include stress due to drought, soil nutrient availability, toxicity and salinity. But there is also variation in nutrient use efficiency, which is not recognized and utilized enough at present. Currently, maximum yield and resistance to pests and diseases still have priority in breeding programmes, but breeding for other attributes should not be ignored. Modern techniques, such as gene transformation, show promise. Selecting genes, e.g. from wild relatives, gives opportunity to breed plants adapted to use nutrients more effectively. Such extensive gene resources have not yet been fully screened and systematically tested by plant breeders for improving crop cultivars.

To avoid the constraints due to climate and crop nutrition, there exist or are being developed efficient strategies and working recommendations. It is the important and responsible task of farm advisors to inform and teach farmers about the necessity and possibility of modern farming without causing deterioration of their soils and the environment.

In conclusion another statement from Norman E. Borlaug is worth remembering.

> *"For those of us on the food production front, let us remember that world peace will not - and cannot - be built on empty stomachs. Deny farmers access to modern factors of production - such as improved varieties, fertilizers and crop protection chemicals - and the world will be doomed not from poisoning, as some say, but from starvation and social chaos."*

10. General reading and references

10.1. General reading

Epstein, E. and Bloom, A.J. (2005). *Mineral Nutrition of Plants: Principles and Perspectives*. 2nd edn. John Wiley, New York.

Marschner, H. (1995). *Mineral Nutrition of Higher Plants*. 2nd edn. Academic Press, London and New York.

Mengel, K. and Kirkby, E.A. (1987). *Principles of Plant Nutrition*. 4th edn. International Potash Institute, Horgen, Switzerland.

Wild, A. (ed) (1988). *Russell's Soil Conditions and Plant Growth*. 11th edn. Longman Scientific & Technical, Harlow, England.

10.2. References

Alam, M.M., Ladha, J.K., Khan, S.R., Foyjunnessa, H., Khan, A.H. and Buresh, R.J. (2005). Leaf color chart for managing nitrogen fertilizer in lowland rice in Bangladesh. *Agronomy Journal* 97, 949-959.

Amberger, A. (1988). Report on agricultural production in the Central Chaco of Paraguay. GTZ, Eschborn, Germany

Amberger, A. (1990). Urea decomposition in soil and NH_3-losses. VDLUFA Series Nr.32, Darmstadt, Germany.

Amberger, A. (1992). Mobilization of rock phosphates in soil by root exudates and fertilization techniques. *In: Phosphorus in Life and Environment*. World Phosphate Institute (IMPHOS), Casablanca, Morocco.

Amberger, A. (1998). Plant response under saline conditions. *In: Proceedings International Symposium on Sustainable Management of Salt-affected Soils in the Arid Ecosystem*, Cairo, Egypt.

Amberger, A. and Singh, C.P. (1994). Effect of humic substances on solubilization of rock phosphates incubated in wheat straw. *In: Humic Substances in the Global Environment and Implications for Human Health*. Elsevier Scientific, London.

Badraoui, M. and Agbani, M. (1992). Chemistry and mineralogy of potassium in Moroccan soils: implications for fixation and release. Actes IAV. Institut Agronomique et Vétérinaire Hassan II, Rabat, Morocco.

Bernstein, L. (1970). *Salt Tolerance of Plants*. Agricultural Information Bulletin 283, USDA, USA.

Besoain, E.M., Rojas, C.W. and Montenegro, A.B. (1999). Las rocas fosforicos y sus posibilidades de uso agricola en Chile. Colleccion libros num. 2. INIA, Santiago, Chile.

Bornemiza, E. and Alvarado, A. (1975). Soil management in tropical America- Proceedings CIAT Colombia 1974. North Carolina State University, USA.

Cakmak, I. (2004). *Identification and Correction of Widespread Zinc Deficiency in Turkey - a Success Story*. Proceedings No. 552. The International Fertiliser Society, York, UK.

Cakmak, I., Vilmaz, A., Kalayci, M., Ekiz, H., Torun, B., Erenoglu, B. and Brun, J.H. (1996). Zinc deficiency as a critical problem in wheat production in Central Anatolia. *Plant and Soil* 180, 165-172.

Cisse, M. (2001). Impact of azolla on urea-N cycling in flooded rice in comparison to and in combination with fertilizer placement, application of potassium chloride and biocides. Dissertation, University Göttingen.

Denich, M., Vielhauer, K. and Hedden-Dunkhorst, B. (2002). New technologies to replace "Slash and Burn" in the Eastern Amazonas. Center for Development Research, Bonn, Germany.

Dobermann, A., Witt, C., Dawe, D., Abdulrachman, S., Gines, H.C., Nagarajan, R., Satawathananont, S., Son, T.T., Tan, P.S., Wang, G.H., Chien, N.V., Thoa, V.T.K., Phung, C.V., Stalin, P., Muthukrishnan, P., Ravi, V., Babu, M., Chatuporn, S., Sookthongsa, J., Sun, Q., Fu, R., Simbahan, G.C. and Adviento, M.A.A. (2002). Site-specific nutrient management for intensive rice cropping systems in Asia. *Field Crops Research* 74 (1), 24-37.

Dobermann, A., Witt, C., Abdulrachman, S., Gines, H.C., Nagarajan, R., Son, T.T., Tan, P.S., Wang, G.H., Chien, N.V., Thoa, V.T.K., Phung, C.V., Stalin, P., Muthukrishman, P., Ravi, V., Babu, M., Simbahan, G.C. and Adviento, M.A.A. (2003). Soil fertility and indigenous nutrient supply in irrigated rice domains of Asia. *Agronomy Journal* 95 (4), 913-923.

El-Fouly, M.M. and Abdalla, F.E. (1996). Micronutrients with macro effects. GTZ Office, Germany and National Research Council, Cairo, Eygpt.

El-Fouly, M.M., Fawzi, A.F. and El-Sayed, A. (1995). Optimizing fertilizer use in oranges through fertigation. International Symposium on Fertigation, Technion. Haifa, Israel.

El-Fouly, M.M. and Salama, Z.H. (1999). Can foliar fertilization increase plant tolerance to salinity? *Nutrient Management under Salinity and Water Stress*. Technion, Haifa, Israel.

El Gala, M.M. and Amberger, A. (1988). Root exudates and the ability of corn to utilize insoluble sources of iron. *Journal of Plant Nutrition* 11, 677-690.

FAO (2002). *World Agriculture Towards 2015/2030*. Food and Agriculture Organization of the United Nations, Rome, Italy.

FAO (2005). *The State of Food Insecurity in the World*. Food and Agriculture Organization of the United Nations, Rome, Italy.

FAO/IFA/IFDC. (2003). *Fertilizer Use by Crops*. 5th edn. Food and Agriculture Organization of the United Nations, Rome, Italy.

Greenland, D.S. (1997). *The Sustainability of Rice Farming*. CAB International, Wallingford, UK in association with IRRI, Los Baños, The Philippines.

Hagin, J., Sneh, M. and Lowengart-Aycicegi, A. (2002). *Fertigation, Fertilization through Irrigation*. IPI Research Topics No. 23. International Potash Institute, Horgen, Switzerland.

Halliday, D.J., Trenkel, M.E. and Wichmann, W. (1992). *IFA World Fertilizer Use Manual*. International Fertilizer Industry Association (IFA), Paris, France.

Härdter, R., Rex, M. and Orlovius, K. (2004). Effects of Different Mg Fertilizer Sources on the Magnesium Availability in Soils. *Nutrient Cycling in Agroecosystems* 70, 249-259.

IFDC (1988). *Soil Fertility and Fertilizer Management in Semiarid Tropical India.* International Fertilizer Development Center, Muscle Shoals, Alabama, USA.

IFDC (1994). Annual Report for 1994. International Fertilizer Development Center, Muscle Shoals, Alabama, USA.

IFPRI (2002). *Sustainable Food Security for All by 2020*. International Food Policy Research Institute, Washington, DC, USA.

IPI (1995). *Potassium in Asia - Balanced Fertilization to Increase and Sustain Agricultural Production*. International Potash Institute, Horgen, Switzerland.

IPI (1997). *Food Security in the WANA Region*. International Potash Institute, Horgen, Switzerland.

IPI (2003). *Feed the Soil to Feed the People - the Role of Potash in Sustainable Agriculture*. International Potash Institute, Horgen, Switzerland.

Johnston, A.E. (2000). *Soil and Plant Phosphate*. International Fertilizer Industry Association, Paris, France.

Johnston, A.E. (2001). *Principles of Crop Production for Sustainable Food Production*. Proceedings No. 459. The International Fertiliser Society, York, UK.

Johnston, A.E. and Syers, J.K. (1998). *Nutrient Management for Sustainable Crop Production in Asia*. CAB International, Wallingford, UK.

Johnston, A.E., Poulton, P.R. and Syers, J.K. (2001). *Phosphorus, Potassium and Sulphur Cycles in Agricultural Soils*. Proceedings No. 465. The International Fertiliser Society, York, UK.

Kafkafi, U., Xu, G., Imas, P., Magen, H. and Tarchitzky, J. (2002). *Potassium and Chloride in Crops and Soils: The Role of Potassium Chloride Fertilizer in Crop Nutrition*. IPI Research Topics No. 22. International Potash Institute, Horgen, Switzerland.

Kanwar, J.R. and Mudahar, M.S. (1986). *Fertilizer Sulfur and Food Production*. M. Nijhoff Publishers, Dordrecht, The Netherlands.

Krauss. A. (1993). The role of potassium in fertilizer nutrient efficiency. *In: Potassium Availability of Soils in West Asia and North Africa-Status and Perspectives*. International Potash Institute, Horgen, Switzerland.

Li, M.L., Römheld, V. and George, E. (2001). A test of the significance of mycorrhizal hyphae in utilizing native organic phosphorus in soils from different farming systems. *In: Developments in Plant and Soil Sciences*. Kluwer Academic Publishers, Dordrecht, The Netherlands.

(Note: *Developments in Plant and Soil Sciences is an occasional publication, often the proceedings of a conference, and can be accessed by the Kluwer web site*).

Likens, G.E., Driscoll, C.T., Buso, D.C., Siccama, T.G., Johnson, C.E., Ryan, D.F., Lovett, G.M., Fahey, T.J. and Reiners, W.A. (1994). The biogeochemistry of potassium at Hubbard Brook. *Biogeochemistry* 25, 61-125.

Marschner, H. (1986). *Mineral Nutrition of Higher Plants*. (1st ed.) Academic Press, London, UK and New York, USA.

Marschner, H. (1995). *Mineral Nutrition of Higher Plants*. (2nd ed) Academic Press, London, UK and New York, USA.

Marschner, H. and Römheld, V. (1996). Root-induced changes in the availability of micronutrients in the rhizosphere. *In: Plant Roots, the Hidden Half*. Marcel Dekker, New York, USA.

Meadows, D.H., Meadows, D.L. and Randers, J. (1992). *Beyond the Limits: Confronting Global Collapse, Envisioning a Sustainable Future*. Chelsea Green Publishers, Mills, Vermont, USA.

Mokwunye, A.V. and Vlek, P. (1986). Management of nitrogen and phosphorus in Sub-Saharan Africa. *Developments in Plant and Soil Sciences*. M. Nijhoff Publishers, Dordrecht, The Netherlands.

Pasda, G., Hähndel, R. and Zerulla, W. (2001). The new nitrification inhibitor DMPP (Entec®) - Effects on yield and quality of agricultural and horticultural crops. *In: Developments in Plant and Soil Sciences*, Kluwer Academic Publishers, Dordrecht, The Netherlands.

Peng, S., Garcia, F.V., Laza, R.C., Sanico, A.L., Visperas, R.M. and Cassman, K.G. (1996). Increased N-use efficiency using a chlorophyll meter on high-yielding irrigated rice. *Field Crops Research* 47, 243-252.

Richards, L.A. (1954). *Diagnosis and Improvement of Saline and Alkali Soils*. Handbook No. 60, Salinity Laboratory, US Department of Agriculture, Washington, DC, USA.

Römheld, V. (1993). Genetic variation in root-induced rhizosphere changes: Prospects for efficient use. *In: Genetic techniques for adapting crop plants to lowered fertilizer inputs and nutrition stress*. Commission of the European Communities. Brussels, Belgium.

Römheld, V. and Marschner, H. (1984). Plant induced pH changes in the rhizosphere of "Fe-efficient and Fe-inefficient" soybean and corn cultivars. *Journal of Plant Nutrition* 7, 623-630.

Sanchez, P. A. (1976). *Properties and Management of Soils in the Tropics*. J. Wiley, New York, USA.

Shaviv, A. and Hagin, J. (1993). Interaction of salinity and enhanced ammonium and potassium nutrition in wheat. *In: Optimization of Plant Nutrition*. Kluwer Academic. Publishers, Dordrecht, The Netherlands.

Sillanpäa, M. (1982). *Micronutrients and the Nutrition Status of Soils - A Global Study*. FAO Bulletin No. 48. Food and Agriculture Organization of the United Nations, Rome, Italy.

Tinker, P.B. (1980). The role of rhizosphere organisms in the uptake of phosphorus by plants. *In: The Role of Phosphorus in Agriculture*. ASA, CSSA, SSSA, Madison, Wisconsin, USA.

Trenkel, M.E. (1997). *Controlled-Release and Stabilized Fertilizers in Agriculture*. International Fertilizer Industry Association, Paris, France.

Vilsmeier, K., Bornemiza, E. and Amberger, A. (1987). Urea, ammonium sulfate and dicyandiamide transformations in Costa Rica soils. *Fertilizer Research* 12, 255-261.

Vlek, P.L.G. (1985). Micronutrients in tropical food production. *In: Developments in Plant and Soil Sciences*. M. Nijhoff Publishers, Dordrecht, The Netherlands.

Vlek, P.L.G. and Fillery, R.P. (1984). *Improving Nitrogen Efficiency in Wetland Rice Soils*. Proceeding No. 230. The International Fertiliser Society, York, UK.

Wang, G., Dobermann, A., Witt, C., Sun, Q. and Fu, R. (2001). Performance of site-specific nutrient management for irrigated rice in Southeast China. *Agronomy Journal* 93, 869-878.

Wissemeier, A.H., Linzmeier, W., Gutser, R., Weigelt, W. and Schmidhalter, U. (2001). The new nitrification inhibitor DMPP (Entec®) - Comparison with DCD in model studies and field applications. *In: Developments in Plant and Soil Sciences*, Kluwer Academic Publishers, Dordrecht, The Netherlands.

Zehler, E., Kreipe, H. and Gething, P.A. (1981). *Potassium Sulphate and Potassium Chloride: Their Influence on the Yield and Quality of Cultivated Plants*. IPI Research Topics No. 9. International Potash Institute, Horgen, Switzerland.

Zerulla, W., Pasda, G., Hähndel, R. and Wissemeier, A.H. (2001). The new nitrification inhibitor DMPP (Entec®) for agricultural and horticultural crops-an overview. *In: Developments in Plant and Soil Sciences*. Kluwer Academic Publishers, Dordrecht, The Netherlands.

11. Annex. Plates

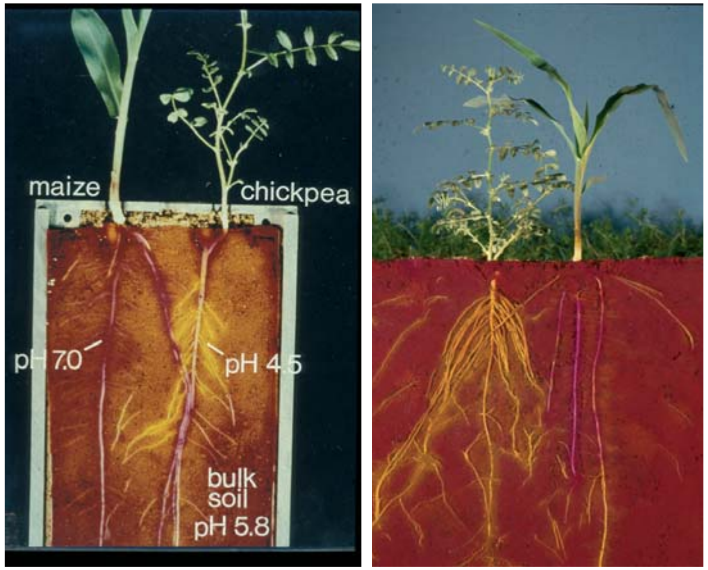

Plate 1. Rhizosphere pH as affected by plant species

Plate 2. Severe water erosion in Sudan

Plate 3. Raising water to the surface by a "saiga" wheel to discharge to a canal, Egypt

Plate 4. Modern irrigation system in Brazil

Plate 5. Drip irrigation system in Egypt

Plate 6. Omission plot setup to assess nutrient requirements in Tamil Nadu, India

Plate 7. A typical Ferralsol in southern Brazil

Plate 8. An Andosol developed in young volcanic ash in Costa Rica

Plate 9. A typical Vertisol in The Philippines

Plate 10. Slash and burn of shrub vegetation in West Africa

Plate 11. A typical Rendzina in Syria

Plate 12. Desert vegetation in Egypt

Plate 13. Puddling a rice paddy in India

Plate 14. A severely salt-affected soil in Egypt

Plate 15. Bare branches and little leaf rosettes due to zinc deficiency in apples

Plate 16. Chlorosis due to iron deficiency in grape vine