MANAGEMENT OF AGRICULTURAL LAND: CHEMICAL AND FERTILITY ASPECTS

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Summary

Fertilizer application is needed to upgrade the natural soil nutrient stock and to compensate for the elements exported from the root zone by harvesting, leaching, erosion and volatilization. There are 20 essential plant elements, including 5 macro-elements (N, P, K, Ca and Mg), required in relatively large amounts, and a remainder of

15 micronutrients, absorbed in much smaller quantities.

Nitrogen (N), phosphorus (P) and potassium (K) are required for plant growth and strengthening of reproductive parts, carbohydrate metabolism, and the activation of some enzymes. N and P are incorporated in the organic material and are not directly available to plants. K is present as elemental K, exchangeable K, or as part of mineral lattices. Under intensive agriculture, these components have to be added to the soil. Commercial fertilizers are supplied as single components, salts or combined products. Calcium (Ca), magnesium (Mg) and sulfur (S), besides their role as a plant nutrient, interfere in the soil acidity and activate a number of plant enzyme systems. The deficiency of any of these elements has a pronounced retarding effect on plant growth.

Micronutrients are required in small amounts by plants. Their presence and availability in the soil is not stable and is affected by pH and their eventual combination with organic compounds (*chelation*). Micronutrients play a major role in the activation of several enzyme systems and in chlorophyll synthesis.
Soil acidity or pH is an expression of available Ca (Mg and K) in the soil, and it interferes in the microbial activity and the mineralization of organic material. It has also an impact on the solubility, viz. availability and toxicity of macro- and micronutrients. It can be corrected by liming. Salinity and alkalinity are harmful for crop production, and these elements have to be eliminated from the soil by leaching whether or not in combination with gypsum application.

1. Introduction

The growing food production to meet the demands of a rapidly increasing world population should mainly come from a substantial yield increase on land already in cultivation. Higher yields involve also higher demands for plant nutrients, and these can generally no more be supplied from natural sources alone. Agricultural statistics indicate that, despite very unequal developments worldwide, the consumption of mineral fertilizer has logarithmically grown since the 1960s, with increases of 500 % in some parts of Europe to 100-250 % in other countries.

Natural plant nutrients come from the weathering and breakdown of geological parent materials and the subsequent release of their chemical components which can be taken up by the vegetation. Only a few soils contain all nutrients required for plant growth. Most other soils have serious deficiencies in one or more of these elements, either because they are not present in sufficient quantities or because they are not available in the proper form.

Under natural conditions - an undisturbed forest or natural grassland for example - the nutrients initially available in the soil material are absorbed by the plant root system and return to the soil at the end of the growth cycle, either as leaves, decayed roots or fallen branches and stems. This is a closed cycle and, unless there is a loss by erosion or runoff, the same nutrients can be taken up again by the new vegetation. In crop farming, however, plant nutrients are absorbed and exported by the crop at harvest, depleting hereby the soil nutrient stock. A rapid replenishment of this stock is required in order to avoid that the biological cycle is broken. This regeneration occurs in first instance through a natural process of on-going cation release from the soil absorption complex and by the *solubilization* of minerals, salts, and secondary compounds in the weathering material. Once this natural source is depleted as well, additional fertilizer must be supplied in order to avoid a chemical degradation of the root zone.

Plant nutrient deficiencies show up in plants in various ways such as stunted growth, foliage color symptoms and reduced yields. Different plants require different kinds and quantities of plant nutrients. Therefore, it is necessary to determine the nature and importance of plant nutrient deficiency and to estimate the nutrient needs, depending upon soil type, kind of plants grown, and yield level desired.

2. Elements Required in Plant Nutrition

Carbon (C), hydrogen (H), oxygen (O), nitrogen (N), phosphorus (P), and sulfur (S) are the major elements of which proteins, hence protoplasm, are composed. In addition, there are fourteen other elements which are essential and beneficial to the growth of some plants: calcium (Ca), magnesium (Mg), potassium (K), iron (Fe), manganese (Mn), molybdenum (Mo), copper (Cu), boron (B), zinc (Zn), chlorine (Cl), sodium (Na), cobalt (Co), vanadium (Va) and silicon (Si). Not *all* are required for *all* plants, but *all* have been found to be essential or beneficial to *some* plants. Each of the twenty elements plays a role in the growth and development of plants, and when present in insufficient quantities can reduce growth and yields (Tisdale *et al*., 1993).

The mineral nutrients are subdivided into two main groups, and plants differ widely in their ability to mobilize and utilize those nutrients from a given soil, as well as to their nutrient requirements: (1) macronutrients, e.g. elements present in amounts more than 0.2 % in plant tissue: N, P, K, S, Ca and Mg; and (2) micronutrients, e.g. elements necessary for plant growth in only small amounts (usually less than several parts per million in plant tissue): Fe, Zn, Cl, Mo, Mn, Cu, B and Co.

3. Managing NPK and Other Macronutrient Levels

In order to grow and produce yields plants need nitrogen, phosphorus, potassium, calcium, magnesium and a number of minor elements in amounts that are in direct relation to their requirements and nutrient exportation by the yield. These elements are to some extent available in the soil, but depending on the quantities required it may be necessary to provide additional amounts.

3.1. Nitrogen

Low yields of maize in the order of 600 to 1200 kg/ha and of wheat in the order of 400 to 800 kg/ha require a supply of N only a little above of what is provided by rain and organic matter *mineralization.* Moreover, such yields do not remove more than 15 kg N/ha from the land in the harvested grain products. Such yields could, therefore, be sustained for relatively long periods under primitive conditions of agriculture with the use of only small amounts of fertilizers. In many important food providing areas in the tropics, these yields prevail and the lack of available nitrogen is the chief limiting factor in the production of crops. To increase yields in the same areas will require the use of N fertilizers or leguminous crops as well as other production inputs.

Natural Fertility Level	**Nitrogen (%)**	**Exchangeable Cations (me/100 g soil)**			
		Ca^{2+}	**Mg^{2+}**	**K^{+}**	**CEC**
Very high	>1	>20	>8	>1.2	>40
High	0.5-1	10-20	3-8	0.6-1.2	25-40
Medium	0.2-0.5	5-10	1.5-3	0.3-0.6	15-25
Low	0.1-0.2	2-5	0.5-1.5	0.12-0.3	5-15
Very low	<0.1	<2	<0.5	<0.12	<5

Table 1: Classification of natural fertility levels in soils, based on the contents of nitrate-N, cation exchange capacity (CEC) and individual exchangeable cations

Nitrogen in the soil originates mainly from three natural sources: (a) the *mineralization* of organic matter and crop residues, (b) the fixation of nitrogen from the atmosphere, largely through biological processes, and (c) additions from rain and other forms of precipitation. The natural N content of a soil provides a good expression of the natural soil fertility (Table 1). Forest soils, especially in the humid tropics, have high nitrogen contents (> 1 % or 1 g N/100g soil); cultivated soils have moderate to low N contents with an overall tendency towards less N in modern agriculture (0.2-0.5 % N); arid soils are low to very low in N (<0.2 % N).

Nitrogen occurs in soils in several forms: organic compounds, nitrate (NO_3^-) and nitrite (NO_2^-) anions, and ammonium (NH_4^+) which can occur as an exchangeable cation. Most soil nitrogen (98 %) is in the organic form and is incorporated in organic material; under this form it is, however, not available to plants. It must therefore first be transformed through microbiological activity into nitrate. In moist warm, well-aerated soils (humid tropics) most nitrogen compounds are converted into NO_3^- which is the form in which N is mainly taken up by plants. Once in the plant, the nitrate is reduced to ammonium-N using the energy provided by photosynthesis. The NH_4^+-N is then combined with so-called carbon skeletons to form amino acids (Tisdale *et al.*, 1993).

Modern agriculture requires high production, and this can only be obtained by the application of high N fertilizers, whether as single components (urea) or compound fertilizers (NPK). A review of the currently used commercial fertilizers and their approximate composition is given in Table 2. An adequate supply of N is associated with a vigorous vegetative growth and a deep green plant color. Excessive quantities of N can, under some conditions, prolong the growing period and delay crop maturity. This is most likely to occur when other plant nutrients are not in sufficient supply. Excessive succulence weakens the fiber strength in cotton, leads to lodging in grain crops, or lowers the sugar content in sugar beets. Plants deficient in nitrogen show a stunted growth and signs of *chlorosis;* the latter phenomenon appears first in the lower leaves, and after some time they turn brown and die.

The quantity and proportion of the soluble N (mainly as ammonium or nitrate) that can be absorbed by the crop is influenced by local site factors, including (a) rooting habits of the crop, (b) the volatile loss processes and the local environmental factors that influence these losses, (c) the vertical movement of nitrate-N, and in some instances the complete removal of the nitrate by leaching, (d) the moisture status in that part of the root zone where the nitrogen resides, and (e) the presence or absence of crop residues which may immobilize nitrogen. The application of N fertilizers combined with P fertilizers facilitates P uptake and plant growth.

3.2. Phosphorus

Phosphorus, though a major plant nutrient, is needed in quantities that are much smaller than those of N and K. Phosphorus has a complicated chemistry, as far as assessment of P levels in the soil and the P fertilizer requirements of the plants are concerned. The element occurs in soils in both organic and inorganic forms, the latter being usually the more important for crop nutrition. Inorganic P can occur as various compounds of Ca, Fe and Al, in solution, in surface films, in the solid state, or as exchangeable phosphate anions held by the positive charges on the edges of clay minerals.

Plants absorb most of their P as HPO_4^- and $H_2PO_4^-$ ions or as soluble organic phosphates which are a direct degradation product of the soil organic material. Phosphorus availability in soils is however very variable, as it depends on mineral soil composition, amount of organic material and on its rate of decomposition, morphological soil properties (texture in particular), previous soil management and local climatic conditions. It is, moreover, difficult to rate the natural soil fertility in terms of its P content because laboratory extraction methods vary widely, and the obtained values differ greatly with the analytical method and soil pH. In neutral and basic soils (Olsen method, 0.5M $NaHCO_3$) the critical level is at 5 ppm; for acid soils this critical value varies between 15 ppm (Bray method, Dilute HCl/NH_4F) and 20 ppm (Truog, Dilute H_2SO_4). More information on the effect of extraction methods used can be found in Landon (1984).

Plant availability of P in the soil is highly dependent on soil pH (for more details, see section 5). Tropical soils rich in free iron and aluminum have a high phosphate-fixing capacity, especially at low pH. With pH above 5.5, however, P becomes more soluble and is available to plants. The best availability is at pH levels between 6 and 7. Above 7 and in the presence of calcium, phosphorus tends again to become less soluble; the least solubility level is reached at pH 8.5.

A review of the most commonly applied commercial P-fertilizers and their approximate composition is given in Table 2. An adequate supply of P at planting stage or very early in the vegetative growth stage strengthens its reproductive parts and seed formation. Moreover, it may hasten plant maturity, gives greater strength to cereal straw and is said to improve disease resistance of certain fruits, forages and vegetables. Deficiency symptoms are expressed by a purple discoloration of older leaves and of leaf edges.

Name	Chemical Formula	Approximate composition (%)					
		N	P	K	Ca	Mg	S
Nitrogen fertilizers							
Ammonia	NH_3	82	-	-	-	-	-
Aqua ammonia	NH_3	15-30	-	-	-	-	-

Ammonium chloride	NH_4Cl	26-28	-	-	-	-	-
Ammonium nitrate	NH_4NO_3	33-34	-	-	-	-	-
Am. nitrate- sulfate	$NH_4NO_3 + (NH_4)_2SO_4$	26-30					5-12
Ammonium sulfate	$(NH_4)_2SO_4$	21	-	-	tr	-	24
Calcium cyanamide	$CaCN_2$	20-22	-	-	40	tr	tr
Calcium nitrate	$Ca(NO_3)_2$	15	-	-	19-21	2	-
Sodium nitrate	$NaNO_3$	16	-	tr	tr	tr	tr
Urea	$CO(NH_2)_2$	46	-	-	-	-	-
Urea S-coated	$CO(NH_2)_2 + S$	35-40	-	-	-	-	7-10
Phosphorus fertilizers							
Calcium metaphosphate	$Ca_2P_2O_7$	-	27	-	19	-	-
Dicalcium phosphate	$CaHPO_4.2H_20 + CaHPO_4$	-	17-23	-	19-29	-	-
Tricalciumphosphate	$Ca_3(PO_4)_2$	-	12	-	20	-	-
Phosphoric acid	H_3PO_4	-	22-33	-	tr	-	-
Rock phosphate	-	-	11-17	-	33-36	-	-
Single Superphosphate	$Ca(H_2PO_4)_2.H_20 + CaSO_4.2H_2O$	-	7-10	tr	13-20	tr	12
Triple superphosphate	$Ca(H_2PO_4)_2.H_2O$	-	18-22	tr	9-14	tr	1
Potassium fertilizers							
Potassium chloride	KCl	-	-	50-52	tr	tr	tr
Potassium nitrate	KNO_3	13	-	37	tr	tr	tr
Potassium phosphate	K_3PO_4	-	18-22	29-45	-	-	-
Potassium sulfate	K_2SO_4	-	-	40-43	-	1	18
N-P fertilizers							
Mono-ammonium phosphate	$NH_4H_2PO_4$	11	21	-	2	tr	5
Di-ammonium phosphate	$(NH_4)_2HPO_4$	18-21	20-23	-	-	-	-
Urea ammonium phosphate	$CO(NH_2)_2 + (NH_4)_2HPO_4$	25-34	7-15	-	-	-	-
Urea ammonium polyphosphate	$CO(NH_2)_2 +$ $(NH_4)_3HP_2O_7 +$ $NH_4H_2PO_4$	22-30	13-19	-	-	-	-
Urea phosphate	$CO(NH_4)_2 + H_3PO_4$	18	20	-	-	-	-
Calcium-Magnesium fertilizers							
Magnesium chloride	$MgCl_2$	-	-	-	2	8-9	-
Magnesium oxide	MgO	-	-	-	-	42+	-
Kieserite	$MgSO_4.H_2O$	-	-	-	-	17	-
Calcium sulfate (gypsum)	$CaSO_4.2H_2O$	-	-	-	23	-	18

* Tr = traces.

Table 2: Name, chemical formula and approximate composition of the main commercial fertilizers

3.3. Potassium

Potassium occurs in three different forms in the soil, excluding that found in the soil fauna and flora: (1) K in the soil solution; this is in equilibrium with exchangeable K^+ and is therefore difficult to distinguish from it; (2) exchangeable K^+, which is affected by clay content, the intensity of mineral decomposition, and the quantity of fertilizers applied; (3) K fixed on or retained between clay lattices in minerals such as illite, micas and feldspars. The first two forms are directly available to plants. Potassium fertilizer is added to soils in the form of a soluble salt, e.g. K chloride, sulfate or nitrate. The natural fertility level of soils in terms of their K content is displayed in Table 1.

Plant requirements for K are relatively high because it is absorbed by plants in larger amounts than any other nutrient except N. The element seems however to be more catalytic to plant growth than to act as a direct building stone. Tisdale *et al.* (1993) consider that it is essential to the following physiological functions: (1) carbohydrate metabolism and starch formation; (2) nitrogen metabolism and synthesis of proteins; (3) regulation of the activities of various essential elements; (4) neutralization of some organic acids; (5) activation of various enzymes; (6) promotion of the growth of meristemic tissues, and (7) adjustment of stomatal activities and water relations.

When potassium is in short supply a number of characteristic deficiency symptoms can be observed in crops, such as: *chlorosis* or *necrosis* of leaf edges, weak straw in grain crops, yield reduction, reduced resistance to plant diseases, poor quality of fruits and vegetables, reduced photosynthetic activities, etc.

The natural fertility classification of soils in terms of their K content is based on a combination of: (a) exchangeable K^+ content and (b) ratio between K and Ca^{2+} plus Mg^{2+}. It is generally accepted that the absolute exchangeable K^+ content should be 0.10-0.12 me/100g soil (Table 1). Crops that tolerate values below 0.10 me K: are cassava, millet and groundnuts; crops that show obvious deficiencies at this level are: pineapple, bananas, coffee, cacao, oil palm. Sugarcane is a very K-exacting crop and requires at least 0.18 me K/100g soil.

The relative importance of K on the exchange complex should be at least 2 % in general, 4 % under intensive cropping and 5 % for fruit trees and K-loving crops such as potato. In addition, the Mg/K ratio should be above 3 and the Ca + Mg/K ratio higher than 25.

3.4. Calcium

Calcium is required by all higher plants, and is absorbed as Ca^{2+} ion. The element has an impact on protein synthesis by its enhancement of the uptake of nitrate-N, and interferes in the activity of certain enzyme systems. It is found in abundant quantities in the leaves; it may also occur in ionic form in cell saps. It is part of the cell wall, and therefore the deficiency of calcium manifests itself in the failure of terminal buds and in the apical tips of roots to develop.

Calcium can be present in the soil as free calcium carbonate ($CaCO_3$) and as soluble and exchangeable Ca^{2+} on the base complex. It occurs in relative abundance in most temperate soils, but is mostly absent in highly weathered tropical soils. Still, in many cases it remains the most common cation on the complex. The calcium status of soils is illustrated in Table 1. Values below 2 me/100 g are considered low, though not always critical. Calcium deficiency to plants occurs in fact only in soils with low cation exchange capacity and pH below 5.5, or under conditions where high natural K reserves or excessive Na contents inhibit Ca uptake. The most commonly used commercial Ca-fertilizers and their approximate compositions are listed in Table 2.

Calcium plays a double role in soil fertility: as a plant nutrient at the same level as N, P and Mg, and as a regulator of the soil pH which determines to a large extent the solubility, toxicity and absorption of various soil components (for more details, see section 5).

3.5. Magnesium

Magnesium is the only mineral constituent of the chlorophyll molecule, and in this respect its importance is obvious; appreciable quantities of the mineral may also be found in seeds. Magnesium seems to be related to the phosphorus metabolism and is considered to be specific in the activation of a number of plant enzyme systems. It is absorbed by the roots in the form of the ion Mg^{2+}.

In the soil Mg is often second in concentration on the exchange complex. Levels above 0.5 me/100g are adequate (Table 1), except for Mg-accumulating crops, such as citrus, which need a slightly higher supply. Ca/Mg ratios on the exchange complex (and expressed in me/100 g soil) should be between 3 and 5. Above 5 Mg might become increasingly unavailable, and with high pH, also P uptake might be inhibited. Below 3 the P uptake is hampered. These ratios can be corrected through the application of dolomite (calcium-magnesium carbonate), lime (calcium carbonate); gypsum (calcium sulfate) or any other adapted commercial fertilizer (Table 2).

Magnesium is a mobile element and its deficiency symptoms often appear first in older leaves *as interveinal leaf chlorosis*. In a more advanced stage the leaf tissue becomes pale yellow, before turning brown and necrotic.

3.6. Sulfur

Most of the sulfur present in soils is in the organic form. Decomposition of this form produces inorganic sulfate-S which is available to plants. Inorganic sulfur in soils comes from rainfall (acid rain), fertilizers, and pesticides. In anaerobic soils various sulfides and elemental S can occur. The former may also be found in recent marine deposits; the latter in volcanic soils.

Sulfur is absorbed by plant roots almost exclusively as the sulfate ion SO_4^{2-}. Sulfate-S is present in equal or lesser amounts than phosphorus in plants such as wheat, corn, beans and potatoes, but in larger amounts in alfalfa, cabbage and turnips. Sulfur deficiency has a pronounced retarding effect on plant growth, and is reflected in the field by uniformly *chlorotic* plants and a general stunted growth.

Tisdale *et al*. (1993) have enumerated its specific functions in plant growth and metabolism: (1) it is required for the synthesis of sulfur-containing amino acids and for protein synthesis, (2) it activates certain enzymes, (3) it is a constituent of certain vitamins, (4) it is present in some plant oils, e.g. of mustard and onions, and it increases the oil contents of flax, soybeans and peanuts, (5) it affects the structure of protoplasm and promotes cold resistance of plants, and (6) it is required for nitrogen fixation by leguminous plants.

Analytical data on sulfur content in soils are difficult to interpret because they seldom give a reliable estimate of the S-levels in the soil root zone. The critical limit of available S is generally put at 3 ppm, though this might also depend on the crop tolerance. Cereals and grains for example will flourish in soils that are deficient in S for alfalfa and clover, which themselves are less demanding than cotton, tomatoes and tobacco (Landon, 1984).

3.7. Calculating the Fertilizer Requirements of Crops

The estimation of fertilizer requirements for crops is based on a simple nutrient balance between the nutrient stock available in the root zone and the nutrients required by the crop to attain a certain yield level (Table 3). The difference between both values determines the type and quantity of fertilizers to be applied.

The nutrient reserve of the soil can directly be assessed from the results of soil analysis and the depth of the root zone, i.e. the soil volume explored by the roots. In general, soil rooting depth is considered 30-40 cm for cereals, 40-50 cm for vegetables and 50-70 cm for fruit trees. Assuming that soil bulk density = 1.3 g/cm^3 the total weight of one hectare to a depth of 30 cm is 1.3 x 3 x 10^6 = 3.9 x 10^6 kg (approximately 4 million kg).

The next step is to compare the available nutrients in the root zone with the specific crop requirements. Table 3 summarizes the approximate amounts of major elements which are taken up and exported by the crop at harvest, as collected from different sources (Jones, 1982, Landon, 1984; Euroconsult, 1989; Tisdale *et al*., 1993). These data show that maize, clover, soybeans and sugar beets are very efficient in extracting nitrogen, while cacao, rubber and tobacco absorb only very small amounts of N. Maize, sugar beets and sugarcane require a lot of phosphorus, while bananas, clover, sugar beets, sugarcane and tomatoes are very demanding for potassium.

Crop and anticipated yield (t/ha)	**Removal of nutrients***				
	N	**P_2O_5**	**K_2O**	**MgO**	**S**
Bananas (30 t fruits)	60	15	200		
Cacao (1 t beans)	20	10	15		
Clover (15 t dry hay)	135	40	160	15	15
Groundnuts (1 t nuts, 2.5 t vines)	50-90**	15	25-50	15	10
Irish potatoes (25 t tubers)	90-115	35-45	120-200	5-10	5
Maize (4 t grain, 3.5 t stalks)	135-200	45-80	110-160	25	15
Maize (80 t silage)	110	45	135	25	15

Oats (3.5 t grain, 3 t stalks)	50	20	70	10	-
Oil palm (15 t fresh fruit bunches)	90	20	135	-	-
Paddy rice (4 t grain, 6.5 t straw)	60-90	30	30-60	10	5
Rubber (1.5 t dry rubber)	40	10	25	-	-
Sorghum (3.5 t grain, 3.5 t stalks)	115	45	95-110	20	15
Soybeans (2 t grains, 3 t straw)	125-150	30	40-65	15	10
Sugar beets (40 t roots, 10 t tops)	150	60	200	-	-
Sugarcane (90 t stripped cane)	85	60	180	-	-
Tobacco flue cured (1.5 t leaves)	40	10	70	10	5
Tomatoes (100 t fruits, 2 t vines)	105	40	200	20	30
Wheat (3.5 t grain, 3 t straw)	85	25-30	60-70	10	10

* Conversion factors: P_2O_5 x 0.436 = P; K_2O x 0.830 = K; MgO x 0.603 = Mg
**Most N is taken from the air

Table 3: Approximate nutrient removal of some selected crops at harvest
(Adapted from Jones, 1982; Landon, 1984; Euroconsult, 1989; Tisdale *et al*, 1993)

The type and quantity of fertilizers that have to be supplied is determined by the balance between the nutrient stock in the soil and the crop requirements on one hand, and by the fertilization efficiency; the latter corresponds to the percentage of added fertilizers that is effectively taken up by the plant. In reality, and in order to avoid a too poor basic soil fertility, it is usually advised to build up first a reasonable nutrient stock in the soil and then, after each crop cycle, to compensate for the exported nutrients. In general, most of the latter applications are done at 2 or 3 specific periods in the growth stage. In sandy soils with a low cation exchange capacity more frequent applications might be recommended.

The calculation explained above is, unfortunately, complicated by the doubts about the effectiveness of the fertilizers applied, in particular with respect to their behavior in the soil. Pertinent questions in this respect are: How much of the fertilizers applied is leached or volatilized? How much is fixed by the soil particles? Is the part fixed by the clay and humus compounds gradually released, or remains it immobilized? The answer to these questions depends often on local conditions. Therefore, the applications should be some 10-20 % above the calculated levels, especially for nitrogen.

Leaching of the element depends on the texture and permeability of the soil (a sand will allow for a stronger leaching than a clay), on the rainfall regime (the more rain the more important the leaching), as well as on the nature of the element itself (N and K are more mobile than P). *Volatilization* affects mainly nitrogen, but it depends not only on the element but also on the form under which the fertilizer has been supplied, and on ambient climatic conditions (soil temperature in particular). Topdressing of urea for example can result in substantial N losses to the atmosphere. Such losses can be very serious if urea or ammonium-N fertilizers are applied to calcareous soils during periods of high temperature or when the soil is undergoing drying. *Nutrient fixation* and subsequent gradual release or immobilization varies with the particular element and with the soil pH. In tropical soils for instance which are rich in aluminum and iron oxides, phosphorus becomes fixed on the soil components at pH levels below 5.5. Hence, they form less soluble precipitates and become unavailable to the crop. Making P available to crops under those situations is thus not necessarily achieved by supplying additional P but by liming the soil and raise the soil pH above the critical pH level. The role of pH in nutrient efficiency is discussed in more detail in chapter 5.

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Biographical Sketch

Willy Verheye is an Emeritus Research Director at the National Science Foundation, Flanders, and a former Professor in the Geography Department, University of Ghent, Belgium. He holds an MSc. in Physical Geography (1961), a PhD. in soil science (1970) and a Post-Doctoral Degree in soil science and land use planning (1980).

He has been active for more than thirty-five years, both in the academic world, as a professor/ research director in soil science, land evaluation, and land use planning, and as a technical and scientific advisor for rural development projects, especially in developing countries. His research has mainly focused on the field characterization of soils and soil potentials and on the integration of socio-economic and environmental aspects in rural land use planning. He was a technical and scientific advisor in more than 100 development projects for international (UNDP, FAO, World Bank, African and Asian Development Banks, etc.) and national agencies, as well as for development companies and NGOs active in inter-tropical regions.