TABLE 8
Major soil groups of the FAO world soils map and USDA equivalents

No.	Type of soil	Soil order under	
		FAO/UNESCO	USDA
1.	Organic soils, consisting largely of organic matter	Histosols	Histosols
2.	Soils formed by human influence	Arthrosols	Plaggept
3.	Mineral soils, mainly formed by parent material		
	- Volcanic soils, often dark coloured	Andosols	Andisols
	- Shifting sands, like desert sand dune soils	Arenosols	Psamments
	- Dark swell–shrink clay soils of the subtropics	Vertisols	Vertisols
4.	Mineral soils, mainly formed by topography		
	- Soils in level lowlands, like young alluvial soils	Fluvisols	Fluvents
	- Waterlogged soils in level lowlands	Gleysols	Aquept
	- Mountainous soils, like shallow soil on hard rock	Leptosols	Umbrept
	- Poorly developed deeper soils in elevated regions	Regosols	Inceptisols
5.	Recently developed mineral soils, from the tropics to the polar regions	Cambisols	Tropept
6.	Mineral soils formed by climate/vegetation in humid tropics		
	- Strongly weathered soils, irreversibly hardened, laterite	Plinthosols	Udox
	- Deeply weathered acid loams, red/yellow due to iron oxides	Ferralsols	Oxisols
	- Strongly leached very acid soils with clay transfer	Acrisols	Ultisols
	- Strongly weathered soils of the seasonally dry tropics	Lixisols, Nitisols	Oxisols, Alfisols
7.	Mineral soils formed by climate/vegetation in arid regions		
	- Saline soils, with high content of soluble salts	Solonchaks	Salid
	- Sodic soils, with a high percentage of adsorbed Na	Solonetz	Argid
	- Soils with gypsum accumulation	Gypsisols	Gypsid
	- Soils with carbonate accumulation	Calcisols	Calcid
8.	Mineral soils formed by climate/vegetation in steppe region		
	- Brown chestnut soils, in the driest steppe areas	Kastanozems	Ustoll
	- Black earths, with deep dark topsoil	Chernozems	Udoll
	- Soils of prairie regions, e.g. degraded chernozems	Phaeozems	Boroll
	- Soils with high humus content, e.g. grey forest soils	Greyzem	Mollisols
9.	Mineral soils formed by climate/vegetation in subhumid regions		
	- Brown soils, base rich, clay transfer; similar to Podzoluvisols	Luvisols	Alfisols
	- Poorly drained, low-lying soils	Planosols	Alboll
	- Acid soils with ash-grey layer above iron oxide horizon	Podzol	Spodosols
	- Brown soils, base rich, clay transfer; similar to Podzoluvisols	Luvisols	Alfisols
	- Poorly drained, low-lying soils	Planosols	Alboll
	- Acid soils with ash-grey layer above iron oxide horizon	Podzol	Spodosols

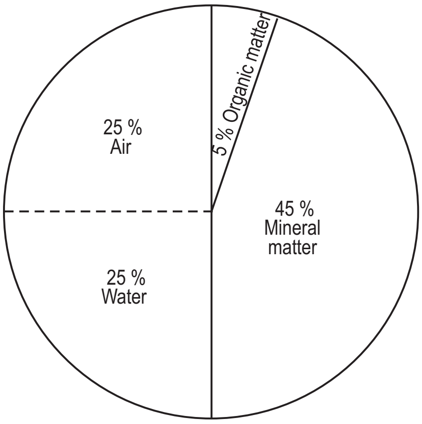
Source: Abridged from Driessen and Dudal, 1991.

that play an important role in plant nutrition. Figure 15 indicates the relative proportions of each of these constituents in an "average soil" on a volume basis.

About 45–50 percent of the volume of a normal soil consists of mineral matter, 1–5 percent is organic matter and the remaining 50 percent consists of open pore spaces that are shared by air and water. In a very dry soil, most of these pores are full of air, while in a saturated soil, they are filled with water. Ideally, air and water occupy about equal space, the air residing in the larger pores and water in the smaller ones. Both are needed for the soil to serve as a medium for plant growth. The organic matter and the pores also house a variety of plant and animal life ranging from microscopic bacteria to earthworms and rodents.

Of the various soil components, the mineral matter changes little during a farmer's lifetime. The organic matter can be increased, maintained or depleted depending upon the amounts of organic manures used and the rate at which these are decomposed. The air–water status can change on a day-to-day or even hourly basis.

FIGURE 15
The average proportion of various constituents in a common soil on volume basis



Soil mineral matter

The soil mineral matter ranges from large pieces of gravel, pebbles and nodules to small grains of sand, silt and clay particles. In addition, there are various oxides, sulphates, silicates and carbonates. The mineral matter on the earth's surface is made up largely of oxygen (47 percent) and Si (28 percent). Only eight elements are present in amounts greater than 1 percent. Among the plant nutrients, the most abundant are not N or P but Fe, Ca, K and Mg.

The difference in size between a coarse sand particle (2.0–0.2 mm diameter) and fine clay (less than 0.002 mm) is a thousandfold. The small size of clay particles gives a very large reactive surface area. While all the mineral fractions determine the texture and waterholding capacity (WHC) of a soil, the sand fraction does not do much. The silt acts as a storehouse of certain nutrients, such as K, while the clay fraction is the most active and a class by itself. As described blow, clay particles along with organic matter give the soil its CEC – a property of great importance from a nutrient management point of view.

Some common minerals formed in soils are listed below on the basis on their degree of solubility (Bolt and Bruggenwert, 1976):

- minerals of high solubility:
  - nitrates,
  - chlorides,
  - bicarbonates,
  - sulphates except calcium sulphate;
- minerals of intermediate solubility:
  - gypsum (calcium sulphate),
  - calcite (calcium carbonate),
  - pyrite (under reduced conditions);
- minerals of low solubility:
  - apatite (tricalcium phosphates),
  - oxides and hydroxides of Si, Al and Fe,

- silicates of Ca, Ma and K.

Saturated solutions of salts with a high solubility inhibit plant growth because of high osmotic pressure. These salts in solid phase are only present in significant quantities under exceptional circumstances (e.g. deserts and in saline or sodic soils). Minerals of intermediate solubility are those with a saturated solution not inhibiting plant growth but their solubility is high enough to contribute significantly to the nutrient composition of the soil solution. The minerals of low solubility contribute to plant nutrient supply only in the long term. Minerals of the silicate, phosphate and oxide groups are almost the end point of the weathering. The fraction of soil mineral matter that contributes to nutrient supply is that which has a moderate degree of water solubility or that with a relatively high specific surface area (surface area / unit weight).

Soil organic matter

Most soils are of mineral origin, but their topsoil contains organic matter that, in spite of its low content, is of great importance to many aspects of soil fertility and plant growth. Soil organic matter (SOM) can range from less than 1 percent in many tropical arid and semi-arid soils of the plains to 5 percent or more in temperate regions or under forest vegetation. The average composition of SOM is 47 percent C, 44 percent O, 7 percent H, 2 percent N and very small amounts of other elements. More than half of SOM consists of carbohydrates, 10–40 percent is the resistant material lignin and the rest consists of compounds of N.

The whole complex of organic matter along with soil organisms and soil flora is of vital importance to soil fertility. SOM contains the well-decomposed fine humus fraction, small plant roots, and members of the plant (flora) and animal (fauna) kingdoms. SOM plays a role far greater than its share of the soil volume. It is a virtual storehouse of nutrients, plays a direct role in cation exchange and water retention, releases nutrients into the soil solution and produces acids that affect the fixation and release of other nutrients.

SOM or “humus” reaches equilibrium during soil formation. Wet and/or cold soil conditions tend to increase the humus content, whereas high temperatures of tropical climates and cropping procedures promote its decomposition. The C:N ratio provides a general index of the quality of SOM, being in the range of 10–15:1 for fertile soils. When organic manures or green manures are added, these become a part of the organic pool of the soil.

Soil pore space

Soil volume that is not occupied by mineral or organic matter is referred to as pore space. This is shared by soil water, soil air and soil life. It has about ten times more CO_2 than the atmosphere. This CO_2 is produced as a result of breathing (respiration) by roots and soil micro-organisms. The ratio of pore space to the volume of solid material in the soil is termed the pore space ratio (PSR). It is an important soil property that determines the dynamics of air, water, temperature and nutrients and also the available root space and ease of working the soil.

SOIL PROPERTIES AND PLANT REQUIREMENTS

Plants need anchorage, water and nutrients from the soil but are sensitive to excesses of growth-impeding substances in the soil. The supply and uptake of nutrients from the soil is not a simple process but requires a suitable combination of various soil properties:

- physical properties (depth, texture, structure, pore space with water and air);
- physico-chemical properties (pH and exchange capacity);
- chemical and biological properties (nutrient status, their transformation, availability and mobility).

A major objective of having the most suitable soil physical, chemical and biological conditions is to provide the most favourable environment for the roots to grow, proliferate and absorb nutrients.

Soil physical properties

Soil physical properties largely determine the texture, structure, physical condition and tilth of the soil. These in turn exert an important influence on potential rooting volume, penetrability of roots, WHC, degree of aeration, living conditions for soil life, and nutrient mobility and uptake. These are as important as soil chemical properties.

Soil depth

Fertile soils generally have a deep rooting zone, which ideally is a minimum of about 1 m for annual crops and 2 m for tree crops. This soil volume should contain no stony or densely compacted layers or unfavourable chemical conditions that impede deep root growth. In addition, the topsoil, which is rich in humus and soil life and the main feeding area for the roots, should be at least 20 cm deep. In practice, many soils have limitations with respect to rooting depth but these can generally be improved by suitable amelioration.

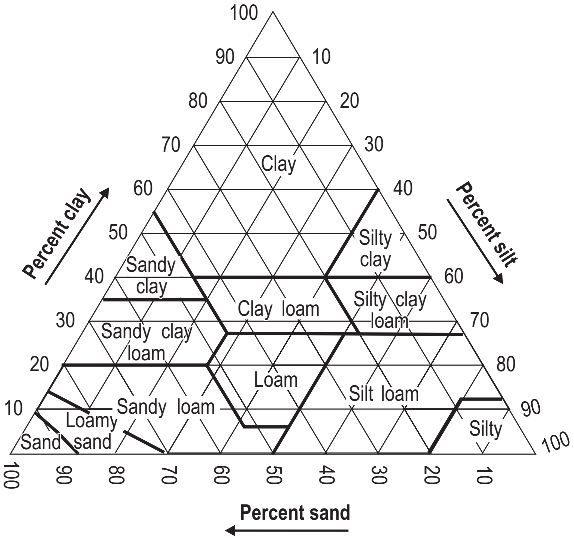
Soil texture

The term texture designates the proportion of different particle size fractions in the soil. Soil texture is primarily represented by its mineral fraction; the organic matter is usually ignored during texture evaluation. Of special importance to soil fertility is the percentage of soil particles of less than 2 mm in diameter, which constitute the fine soil. Fine soil is composed of particles in three size groups: sand, silt and clay. International size units used to classify soil particles in terms of their mean diameter are:

- gravel (> 2.0 mm);
- coarse sand (2.0–0.2 mm);
- fine sand (0.2–0.02 mm);
- silt (0.02–0.002 mm);
- clay (< 0.002 mm).

Based on the relative proportions of these components, soils are classified into different textural classes, such as sandy, loamy or clay soils, and several

FIGURE 16
USDA classification of soil texture classes according to proportions of sand, silt and clay



intermediate classes (Figure 16). The size of a particle is not related to its chemical composition, e.g. sand may be just silica or nutrient rich feldspar or apatite. Clay particles are of colloidal size and are of special importance because of their mechanical and chemical activity. They consist of plate-like structures that have large external and internal charged surfaces for exchange of nutrient ions, particularly the positively charged cations. Some common types of clays are kaolinite, illite and montmorillonite.

The texture of a soil can be determined approximately by simple “finger rubbing” of moist samples, or precisely by conducting a mechanical (particle size) analysis in a laboratory. Terms used by farmers and sometimes even by researchers such as “light” for sandy soils and “heavy” for clay soils are not based on the actual weight (the volume weight of sandy soils being greater than that of clay soils), but on the practical perception of ease of cultivation as mechanical cultivation requires less energy on a light soil than on a heavy soil.

Soil texture influences to a large extent several components of soil fertility such as the amount of nutrient reserves and their proportion to the available nutrient fraction. It also influences several properties such as aeration, pore space distribution, WHC and drainage characteristics. The broad relation of soil texture with soil fertility can be stated as follows:

- Sandy soils are generally poor in nutrient reserves and have a low WHC, but provide favourable conditions for root growth, soil aeration and drainage of surplus water.
- Clay soils are often rich in nutrient reserves (but not necessarily in plant available forms), have high WHC because of the many medium and small pores, but soil aeration is restricted.
- Loamy soils, like sandy or silty loam, have intermediate properties and are generally most suitable for cropping.

Table 9 lists the effect of various textural classes on different physical properties of a soil. A good soil for plant growth should contain moderate quantities of all the different fractions. As the proportion of any fraction increases, such a soil becomes more suitable for plant growth in some respects and less suitable in other respects. For example, where a soil contains a large proportion of sand, it is well aerated,

TABLE 9
Physical properties of soils related to primary particle size fractions

Physical property	Relative impact of the fraction on the soil property			
	Coarse sand	Fine sand	Silt	Clay
Water holding capacity	Very low	Medium	High	Very high
Capillarity	Very low	Good	Great	Very great
Rate of water movement	Very fast	Fast	Slow	Very slow
	(down)	(down and up)	(down and up)	(down and up)
Absorption capacity (for gases, water and plant nutrients)	Very slight	Slight	High	Very high
Cohesion and plasticity	None	Slight	High	Very high
Relative temperature	Warm	Fairly warm	Cold	Very cold
Aeration	Very good	Fairly good	Poor	Very poor

excessive moisture drains away easily, and the soil is easy to cultivate. However, such a soil retains too little moisture and plants can quickly suffer from moisture stress. Plant nutrients also leach out of such a soil very easily. Where a soil has a high clay content, it retains moisture and plant nutrients well but such a soil is also poorly aerated, becomes easily waterlogged, and is difficult to cultivate. Thus, it is easy to understand why sandy loams (that contain all the particle size fractions in favourable proportions) are considered the most productive agricultural soils.

Soil structure

The individual particles of the fine soil fraction are usually bound together by organic/inorganic substances into larger aggregates. The process, known as aggregation, results in a vastly increased pore space that is occupied by air and water. The three-dimensional arrangement of the different sizes and shapes of soil aggregates is termed soil structure. In contrast to soil texture, it is a rather variable soil property that, from an agronomic point of view, can improve or deteriorate. There are different types of soil structure, e.g.: single grain and granular structure with good water permeability; blocky and prismatic structure with medium water permeability; and platy and massive structure with slow water permeability. The clay particles, some of which have swelling and shrinking properties (as in black clay soils such as Vertisols) depending on water content are important components of structure formation and, therefore, of pore space distribution.

For agricultural use, the best type is a stable or large granular “crumb” structure with biologically formed sponge-like aggregates of 0.1–1 cm formed by earthworms in combination with string-forming fungal hyphae or gum-producing microbes. Such crumbs are stable against wetting and have a good mixture of different pore sizes, which are desirable characteristics of fertile soils. In contrast, crumbly pieces formed by mechanical tillage are usually much less stable. An important feature of good soil structure is its stability against deteriorating processes such as wetting and pressure. Annual cropping with relatively high disturbance of soils often results in some structural deterioration, which can be reversed to different degrees (as in flooded-paddy soils).

The soil pore system with water and air

The solid soil particles leave large and small holes between them, which make the soil a porous system. The PSR determines the dynamics of air, water, temperature and nutrients and also the available root space and ease of working the soil. Because of the large portion of pores in soils, the volume weight of mineral topsoils is only about 1.5 (1 litre of soil = 1.5 kg).

In a soil, there are a wide range of pore sizes present, and the percentage of the total pore space made up of any particular size varies greatly between soil textural classes. The multiple-shaped pore space is filled by water and air in varying proportions depending on the water content of the soil. Ideally, mineral soils should have a pore volume of almost 50 percent with about one-third of this consisting of large pores. The size of pores determines their function:

- Large pores (10–50 µm diameter or even larger): These contain air or provide drainage.
- Medium pores (0.2–10 µm diameter): These contain the available water.
- Small pores (less than 0.2 µm diameter): These also hold water, but because of the high tension (force) with which it is tightly held, this water is not available to the plants.

Soil water

Soil water added by rain or irrigation is stored up to the WHC of the soil, which is also called the field capacity. The WHC denotes the maximum amount of water that a soil can hold after free drainage has ceased. It is the upper limit of available water. The surplus water is drained by large pores. The WHC is a key soil property because all chemical and biochemical processes require water. The capacity to store plant available water varies greatly among soils depending on their texture, depth, structure and humus content. The loamy/silty soils store the highest amounts of plant available water, whereas coarse sands store very little. Clay soils store considerable amounts of water, but a large portion is not available because it is tightly held in very small pores. Soil water is retained by adsorption and capillary forces, which are measured either in kiloPascals or by its related logarithmic pF value (a pF of 3 indicates an average moist soil). Crops generally use 300–800 litres of water to produce 1 kg of dry matter.

Some practical aspects of soil water are:

- Water is held mainly in medium-sized pores, and medium-textured soils hold the highest amounts.
- Only the free or loosely bound portion of water (15–1 500 kPa) is available to plants. Water drains freely from pores with a diameter exceeding 60 µm. Thus, pores in the range 0.2–60 µm are important in retaining plant available water.
- Nutrient ions travel to the roots as part of the soil water (soil solution).
- Roots can extract available water because of their suction forces.
- Maximum soil water storage against gravitational losses is at field capacity (pF of 2.2 = 15 kPa).

- Dry soils at the wilting point of crops have only non-available water left (pF 4.2 = 1 500 kPa).
- The storage capacity within 150 cm depth varies from 40 to 120 mm of rain for most soils.

Soil air

Soil air is generally similar in composition to atmospheric air except that it has 7–10 times higher concentration of CO_2 than does the atmosphere (0.2 percent compared with 0.03 percent).

As a result of the respiration by roots and micro-organisms, the oxygen in the soil air may be consumed quickly and CO_2 produced, which is unfavourable for both root growth and functions. For most crops, the soil air should contain more than 10 percent oxygen but less than 3–5 percent CO_2. A continuous exchange with atmospheric air, termed soil aeration, is required in order to avoid a deficiency of oxygen. In cropped fields, the breaking of surface compaction can assist in this, but it must be done without destroying soil aggregates. In terms of air–water relations, the two extremes are represented by well-aerated sandy soils (excess air and a shortage of water) and the flooded-rice soils (excess water and a shortage of air).

Soil physical properties and root growth

Crop growth requires that nutrients be present in soil in adequate amounts and in suitable forms for uptake. In addition, the nutrients must be supplied to the root surface at a sufficient rate throughout the growth of the crop so that the crop does not suffer from inadequate nutrient supply. This is particularly important during periods of rapid growth when nutrient demands are high. The physical nature of the soil affects the growth of an established plant through its influence on various factors such as aeration and moisture supply. In addition, such physical properties alter the resistance offered to root elongation and enlargement, proliferation and water uptake, which in turn affect plant nutrition. There are at least three important factors that determine the rate of root elongation. These are: turgor pressure within cells, constraint offered by the cell wall, and constraint offered by the surrounding medium. All of these are affected by the soil physical environment in the vicinity of the elongating root. The requirements of plant roots in soils are:

- deep rooting volume, ease of penetration and no restrictions on root growth;
- adequate available plant nutrients from soil reserves, external inputs or from N fixation;
- sufficient available water to support plants and soil life, for nutrient transformations and for nutrient transport to the roots;
- facility for the drainage of excess water from the rootzone to ensure the right air–water balance (except flooded-paddy fields).
- good soil aeration to meet the oxygen requirements of roots and for the removal of surplus CO_2.

TABLE 10
The effect of moisture and of soil compaction on the growth of maize plants

Treatment		Weight of tops	Weight of roots	Weight of total plant	Top:root ratio
Compaction	Moisture		(g)		
Loose	wet	39.4	14.8	54.2	1:0.38
Loose	dry	27.5	9.3	36.8	1:0.34
Compact	wet	16.0	6.5	22.5	1:0.40
Compact	dry	20.1	11.3	31.4	1:0.56

Root growth and the dynamics of water and air are largely dependent on pore space. Root growth occurs within continuous soil pores, within disturbed zones resulting from macro-organism activity and within the soil matrix itself. Pore size distribution is important for root penetration, water retention and aeration. In general, roots take the path of least resistance as they grow in soil. Root growth is reduced where the pore size is smaller than the root diameter because the plant must spend energy to deform the pore. The existence of sufficient continuous pores of adequate size is an important determinant of root growth. Most of the roots are 60 µm or more in diameter. The first-order laterals of cereals may range in size from 150 to 170 µm. In contrast, the root hairs are much smaller than 60 µm.

Bulk density (in grams per centimetre) is an indirect measure of pore space within a soil. The higher the bulk density, the more compact is the soil and the smaller is the pore space. In addition to absolute pore space, bulk density also affects the pore space distribution (according to size). Soil compaction decreases the number of large pores (> 100 µm) and, as these are the ones through which roots grow most easily, compaction can have an adverse effect on root growth. The effect of bulk density may be altered considerably by changing the moisture content of the soil. As the pore space can be filled with either air or water (containing nutrients) and there is an inverse relationship between these two parameters, an increase in moisture content means a decrease in air-filled pores.

In general, a decrease in soil moisture content reduces root growth even though more space is physically available to roots. Moreover, where the soil moisture content exceeds field capacity, this leads to poor aeration and root growth declines. Table 10 lists the effects of bulk density (compaction) and aeration (moisture) on plant growth. It shows that compaction of the soil under wet conditions can result in a marked decrease in root and top growth through a combination of mechanical impedance and aeration problems. There is a positive response to moisture in loose soil because the large pores drain easily and plant can suffer from a shortage of water. In contrast, adding water to the compact soil reduces root growth because of a lack of air in the soil pores caused by the displacement of air by water.

Organic matter and soil fertility

The effect of SOM on soil fertility far exceeds its percentage share of the soil volume. Organic matter affects soil fertility and productivity in many ways:

- It promotes soil structure improvement by plant residues and humic substances leading to higher WHC, better soil aeration and protection of soil against erosion.

- It influences nutrient dynamics, particularly:
  - nutrient exchange, thus keeping the nutrients in available forms and protecting them against losses;
  - nutrient mobilization from decomposed organic nutrient sources: N, P, S, Zn, etc.;
  - nutrient mobilization from mineral reserves by complex formation or by changes in pH and redox potential;
  - immobilization of nutrients on a short-term or long-term basis (reverse of mobilization);
  - nutrient gain as a result of N fixation from the air.
- It influences promotion or retardation of growth through growth hormones.

Organic substances in the soil are important nutrient sources. Moreover, some substances can bring about the mobilization of nutrients from soil mineral reserves by the production of organic acids, which dissolve minerals, or by chelating substances excreted by roots and/or by microbes. Chelates may bind Fe from iron phosphate and, thus, liberate phosphate anions. Organic matter may also have some negative effects, namely the short-term fixation of nutrients such as N, P and S into micro-organisms, which may create a transient deficiency particularly at wide ratios of C with these elements (e.g. C:N, C:P, and C:S ratio). The long-term fixation of these elements into stable humic substances appears to be a loss but it can be beneficial because of its positive effect on soil aggregation and, hence, on soil structure.

Rapid and far-reaching loss of SOM is an important factor in soil degradation. Many of the effects of organic matter are connected with the activity of soil life.

Soil organisms and soil fertility

Soil abounds in the following various types and forms of plant and animal life:

- animal life (fauna):
  - macrofauna (earthworms, termites, ants, grubs, slugs and snails, centipedes and millipedes),
  - microfauna (protozoa, nematodes and rotifers);
- plant life (flora):
  - macroflora (plant roots, and macro-algae),
  - microflora (bacteria, actinomycetes, fungi and algae).

Beyond the soil-forming activities of earthworms, termites and other large soil fauna, the multitude of different soil organisms (colloquially also called soil life) contributes significantly to the soil physical and chemical conditions, especially in the transformation of organic matter and plant nutrients. The rate of transformation of most nutrients into available forms is controlled largely by microbial activity. Their huge number represents an enormous capacity for enzyme-based biochemical processes. A special case is N fixation by N-fixing free-living or symbiotic bacteria. Another case relates to the solubilization of insoluble phosphates by several types of soil micro-organisms (Chapter 5).

Soil micro-organisms have similar requirements of soil conditions for optimal activity in terms of air, moisture and pH, as do crops. In general, fungi are more active under acidic conditions, while bacteria prefer neutral–alkaline reaction. Any improvement in soil fertility for crops should also improve conditions for the activity of soil flora and fauna. Microbial activity not only determines soil fertility but it also depends on good soil fertility.

Soil physico-chemical and chemical properties

Three important physico-chemical characteristics of soil fertility are: (i) soil reaction or pH; (ii) nutrient adsorption and exchange; and (iii) oxidation-reduction status or the redox potential.

Soil reaction

The reaction of a soil refers to its acidity or alkalinity. It is an important indicator of soil health. It can be easily measured and is usually expressed by the pH value. The term pH is derived from Latin *potentia Hydrogenii* and is the negative logarithm of the H^+ ion concentration (logarithm of grams of H^+ per litre). Because of the logarithmic scale used, in reality, the actual degree of acidity has enormous dimensions, e.g. the difference in acidity between pH 4 and 5 is tenfold. Thus, a soil of pH 5 is 10 times more acid than a soil of pH 6 and a soil of pH 9 is 10 times more alkaline than a soil of pH 8.

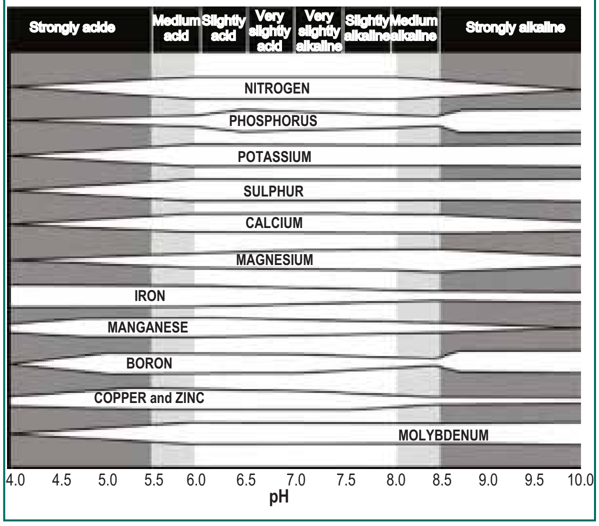
The importance of soil pH is:

- the pH value indicates the degree of acidity or alkalinity of a medium, in this case soil;
- pH 7 is the neutral point, pH of 6.5–7.5 is generally called the neutral range;
- acid soils range from pH 3 to 6.5, alkaline soils from pH 7.5 to 10;
- most soils are in the pH range of 5–8, while the range for plant growth is within pH 3–10;
- the pH of a soil can be altered by amendments and nutrient management practices.

Soil pH is measured in soil/water suspensions. Where dilute calcium chloride solution is used instead of water, the data are lower by 0.5–1.0 of a unit. The pH value obtained is an average of the volume tested. In nature, there is a natural tendency towards soil acidification, the rate of which often increases under leaching, intensive cropping and persistent use of acid-forming fertilizers. Strong acidification leads to soil degradation. However, this can be overcome by the application of calcium carbonate (lime) or similar soil amendments. Unfavourable high pH values, as observed in alkali soils, can be decreased by amendment with materials such as gypsum, elemental S or iron pyrites. Various amendments for acid and alkali soils are discussed in Chapter 5.

Soil reaction is not a growth factor as such but it is a good indicator of several key determinants of growth factors, especially nutrient availability. Soil reaction greatly influences the availability of several plant nutrients. For example,

FIGURE 17
Soil pH and nutrient availability



Note: The wider the bar, the greater the nutrient availability.
Source: Brady and Weil, 1996.

phosphate is rendered less available in the strongly acidic upland soils. The availability of heavy metal nutrients (Cu, Fe, Mn and Zn) increases at lower pH, except for Mo. Although not a nutrient, Al becomes toxic below pH 4.5 (Figure 17). Most plants grow well in the neutral to slightly acid range (pH 6–7) with the dominant cation Ca. Plants are generally more sensitive to strong alkalinity, where the dominant cation is often Na, than to strong acidity where the dominant cation is H. The range of slight and moderate acidity can have special advantages in respect of nutrient mobilization. Soils with very strong acidity (below pH 4.8) contain high levels of soluble Al. Almost no plants can survive below pH 3.

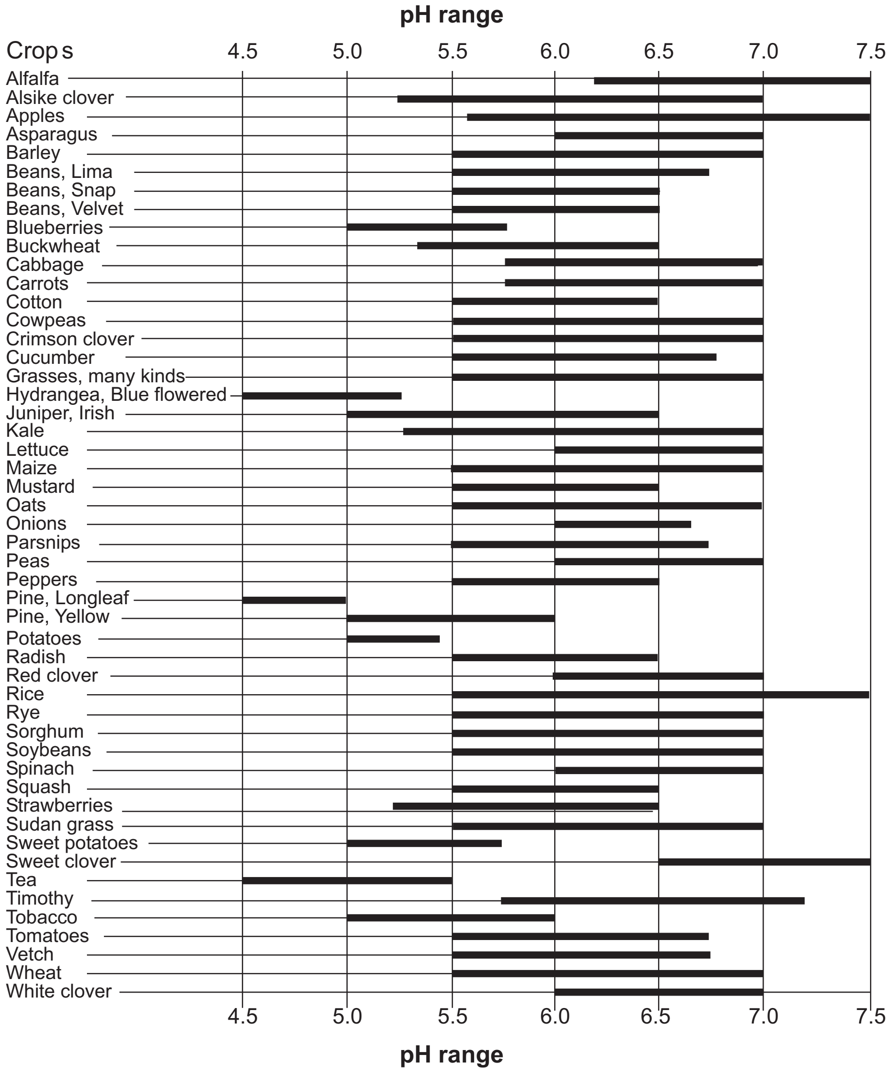
The preference of plants for a certain pH range is often determined by aspects of nutrient requirement and efficiency and not because of the pH as such. For example, oats prefer a slightly acid range because of better Mn supply. Tea bushes benefit from an acid environment. This preference could also be caused by the adaptation of a plant species to a certain environment over time (Figure 18). However, this does not mean that the indicated crops cannot be grown outside the depicted pH range.

Exchange capacity and plant nutrition

Only a small percentage of the available nutrients move freely in the soil solution. Most of them are loosely bound on mineral and organic surfaces in exchangeable form. This mechanism acts as a storehouse both for nutrient cations and anions. Clay minerals, especially illitic and montmorillonitic types, have large negatively charged surfaces on which cations like Ca^{2+}, Mg^{2+} and K^+ are adsorbed and, therefore, protected against leaching. Other particles like oxides and some humic substances also have positive charges and are able to bind anions like phosphate and, to a lesser extent, sulphate. By contrast, nitrate and chloride are hardly bound at all and can be easily lost from the rooting volume by leaching if not taken up by the plant.

The capacity of a soil or any other substance with a negatively charged exchange complex to hold cations in exchangeable form is referred to as its CEC. It is a measure of the net negative charge of a soil and is expressed in me/100 g soil

FIGURE 18
Optimal soil pH for different crops



(old term) or cmol (p+)/kg or cmol/kg (new term). The CEC depends on the type and proportion of clay minerals and organic matter present in the soil. Clay soils have a higher CEC than do sandy soils. Similarly, soils rich in organic matter have a higher CEC than soils that are low in organic matter. Different cations are held on to the exchange sites with differing adsorption affinity or bonding strength (Schroeder, 1984). This determines the ease or the difficulty with which these can be dislodged from the exchange site by cations in the solution. In general, the strength with which different cations are held on the exchange complex is in the following order (which means that Al^{3+} is held most tightly and Na^+ is held most loosely among the cations shown): $Al^{3+} > Ca^{2+} > Mg^{2+} > K^+, H^+, NH^{4+} > Na^+$.

The CEC ranges from less than 10 cmol/kg for sandy soils to more than 30 cmol/kg for clay soils. For average mineral soils, an ideal ratio of cations on the exchange complex would be 75:15:5-3 of Ca:Mg:K. For a soil with an average CEC of 20 cmol/kg, the amounts of exchangeable cations present would be: Ca = 9 000 kg, Mg = 1 000 kg and K = 700 kg/ha. Base saturation refers to the percentage of CEC that is occupied by basic cations. It is an important characteristic of soil fertility. The degree of base saturation is calculated as the ratio:

$$\text{ratio:} \quad \frac{Ca^{2+} + Mg^{2+} + K^+}{Ca^{2+} + Mg^{2+} + K^+ + H^+ + Al^{3-}}$$

If a soil has a CEC of 25 cmol/kg and out of this 3 cmol/kg is occupied by H^+ and the rest by basic cations, then the base saturation will be 88 percent (22/25 × 100). The availability of cations to plants varies according to the strength of bonding with the exchange complex. However, exchangeable cations are generally considered available to plants either directly by contact exchange or more frequently by desorption into the soil solution. In general, soils with a high degree of base saturation are the most fertile ones, provided the exchange complex is not dominated by one particular cation (e.g. Na in sodic soils).

Similarly, the replacement of one anion by another on positively charged soil surfaces or other anion exchange media such as resins is referred to as anion exchange. An example is the exchange of $H_2PO_4^-$ with F^- or of NO_3^- with Cl^-. Anions can enter and exit the soil solution through anion exchange while still remaining in the soil. Anion exchange is of less significance than cation exchange in soil fertility management and plant nutrition. The capacity of a material (soil) to hold anions in exchangeable form is its anion exchange capacity (AEC). It is expressed as centimoles per kilogram of soil or cmol (e^-)/kg. As in the case of cations, different anions are also held on to the exchange complex with varying strength, which is in the order: $PO_4^{3-} > SO_4^{2-} > NO_3^- > Cl^-$.

A decrease in CEC or AEC can result from structural breakdown where clay surfaces become inaccessible or from humus decomposition, but good soil management can reverse this. Table 11 presents a guide to the interpretation of CEC data. The value for each nutrient cannot be considered by itself but in relation to the other ions present. In addition, the rate of its movement to the plant roots is very important. Such rates are determined by soil texture, soil moisture status and nature of the cation, among other factors.

TABLE 11
Ranges of exchangeable cation in soil for the interpretation of cation exchange data

Rating	Exch. Ca	Exch. Mg	Exch. K	Exch. Na	CEC
			(cmol/kg)		
Very high	> 20	> 8	> 1.2	> 2	> 40
High	10–20	3–8	0.6–1.2	0.7–2	25–40
Medium	5–10	1–3	0.3–0.6	0.3–0.7	12–25
Low	2–5	0.3–1	0.2–0.3	0.1–0.3	6–12
Very low	< 2	< 0.3	< 0.2	< 0.1	< 6

Redox potential of the soil

The redox potential is a very important soil property that has a marked influence on the oxidation-reduction state of a soil and, hence, on nutrient dynamics. It is denoted by Eh. The redox potential of a soil varies from -300 mV (strongly reducing condition) to +800 mV in a well-aerated upland soil. The higher the redox potential is, the higher is the oxidizing power of the system. Where the redox potential is high, there is much dissolved oxygen in the soil solution and there is a high proportion of oxidized compounds such as ferric oxide, nitrate and sulphate. Where the redox potential is low, the soil system is deficient in oxygen and there is a greater concentration of reduced forms such as ferrous, ammonium and sulphide. A low redox potential is caused primarily by micro-organisms that break up oxidized compounds and ions in order to obtain oxygen for their metabolism. When the reducing conditions set in, the sequence in which various compounds or ions are set free is: NO_3^-, Mn^{2+}, Fe^{2+}, SO_4^{2-} and, finally, reducible organic matter.

The redox potential is of greatest importance in submerged soils such as under flooded-rice cultivation. As the reducing conditions set in following flooding or ponding, the soil pH moves towards neutrality. In general, the solubility of P increases because of the reduction of iron phosphates; the solubility of Fe and Mn also increases as their less soluble oxidized forms are converted to more soluble reduced forms, e.g. from ferric (Fe^{3+}) to ferrous (Fe^{2+}). Under reduced conditions, the nitrate N is also lost through denitrification.

NUTRIENTS IN SOILS AND UPTAKE BY PLANTS

Soil nutrient sources

Many soils have vast reserves of plant nutrients but only a small portion of these nutrients becomes available to plants during a year or cropping season. Nutrients are present in both organic and mineral forms as stated in Table 6. However, all forms must change themselves to specific mineral ionic forms in order to be usable by plant roots. Thus, in order to become available to plants, nutrients must be solubilized or released from mineral sources and mineralized from organic sources including SOM. Although nutrient mobilization is a rather slow process, it increases sharply with temperature. A temperature increase of 10 °C doubles the rate of chemical reactions. Consequently, the 20–30 °C higher temperature in tropical areas results in chemical transformations (e.g. nutrient mobilization or humus decomposition) at 4–6 times higher the rate in temperate areas.

About 1–3 percent of SOM is decomposed annually and this is a key determinant of N supply. If a fertile soil contains 8 000 kg N/ha in the organic matter (e.g. 2 percent), this corresponds to 160 kg of N transformed from organic N into ammonia, which may then be converted into nitrate. From this amount, crops may utilize about 50 percent, some is taken up by micro-organisms and some lost by leaching, denitrification and volatilization.

As crop yields have increased over the years as a result of technological changes, few soils are able to supply the amounts of nutrients required to obtain higher yields without external inputs. An ideal soil is rich in mineral and organic sources of plant nutrients. In addition, it has the following characteristics:

- It has a strong capacity to mobilize nutrients from organic and inorganic sources.
- It stores both mobilized and added nutrients in forms that are available to plant roots, and protects them against losses.
- It is efficient in supplying all essential nutrients to plants according to their needs.

Practical importance of nutrients

A number of plant nutrients are of large-scale practical importance for successful crop production in many countries. Prominent among these are N, P, K, S, B and Zn. This means that their deficiencies are widespread and external applications are necessary to augment soil supplies for harvesting optimal crop yields while minimizing the depletion of soil nutrient reserves.

N deficiency is widespread on almost all soils, especially where they are low in organic matter content and have a wide C:N ratio. Rare exceptions are soils with very high N-rich organic matter content during the first years of cropping, e.g. after clearing a forest. Widespread N deficiency is reflected in the fact that out of the 142 million tonnes of plant nutrients applied worldwide through mineral fertilizers, 85 million tonnes (60 percent) is N. In addition, substantial external N input is received through organic manures, recycling and BNF.

P deficiency was serious before the advent of mineral fertilization because the native soil phosphate was strongly sorbed in very acid soils or precipitated as the insoluble calcium phosphate in alkaline soils. P deficiencies continue to be a major production constraint in many parts of the world. External input through mineral fertilizers alone was 33.6 million tonnes P_2O_5 in 2002.

K deficiency is most strongly expressed in acid red and lateritic soils or on organic soils that have few K-bearing minerals. Soils rich in 2:1-type clays and those in arid or semi-arid areas are generally better supplied with K than soils in humid regions because of lower or no leaching losses in the former. Ca supply is abundant in most neutral–alkaline soils and, hence, field-scale Ca deficiencies are rare. Where a Ca deficiency occurs, it is mainly in acid soils or because of insufficient uptake and transport of Ca within the plant. Mg deficiency can be widespread in acid soils as a consequence of low supply and leaching losses.

S deficiency was of little practical importance decades ago because of considerable supply from the atmosphere, and widespread use of S-containing fertilizers such as single superphosphate (SSP) and ammonium sulphate. However, S deficiency has developed rapidly in recent years as the atmospheric inputs have declined and high-analysis S-free fertilizers have dominated the product pattern used. The problem has become significant and soil S deficiencies have been reported in more than 70 countries. About 9.5 million tonnes of S are currently applied as fertilizer worldwide (Messick, 2003).

Micronutrient deficiencies are common because of certain soil conditions and have developed at higher yield levels and on sensitive crops. On a global scale, the deficiencies of Zn and B are perhaps of greatest importance. Fe and Mn deficiencies frequently occur on calcareous soils or on coarse-textured soils with neutral or slightly alkaline reaction and rarely on acid soils. In certain areas, Mo deficiencies can even impede the establishment of legume pastures and lessen the potential gains from BNF. On strongly acid soils, there may even be problems of micronutrient toxicities.

Available nutrients in soils

Out of the total amount of nutrients in soils, more than 90 percent is bound in relatively insoluble compounds or is inaccessible within large particles and, therefore, is unavailable for crop use. Only a very small proportion is available to plants at any given point of time. To assess the nutrient supply to crops, it is important to know the amount of available soil nutrients either actually present or likely to be accessible to the plant during a cropping season. All available nutrients must reach the rootzone in ionic forms that plant roots can take up. In order for plants to acquire available nutrients, plant roots must intercept them in the soil or they must move to the root either with the water stream or down a chemical concentration gradient.

Moreover, available nutrients in soils are not a specific chemical entity or a homogeneous pool, but consist of three fractions. In terms of decreasing availability, these are:

- nutrients in the soil solution;
- nutrients adsorbed onto the exchange complex;
- nutrients bound in water-insoluble forms but easily mobilizable nutrient sources.

While the first two fractions are easily available and can be determined by fairly accurate and precise methods, the third fraction comprises a range of substances with varying availability and, therefore, is difficult to assess (described below).

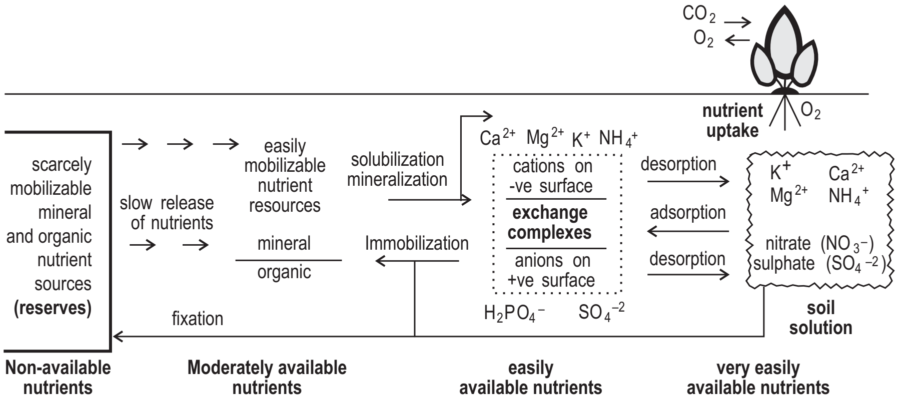
Nutrients in the soil solution

The soil solution is the substrate from which roots take up nutrients. It is comparable with the nutrient solution in hydroponics. Soil solution means soil water containing small amounts of dissolved salts (cations/anions) and some organic substances that is mainly held in medium to small pores. The concentration of these nutrients is very different and varies considerably in time.

The solution of fertile soils may contain 0.02–0.1 percent salts in wet soils but a higher concentration in dry soils. In a neutral soil, the dominant nutrient is generally nitrate (30–50 percent), followed by Ca (20–30 percent), and Mg, K and sulphate-S (about 10 percent each). Ammonium is less than 2 percent and phosphate-P is considerably less than 0.1 percent. In saline and alkali soils, there are large concentrations of Na, chloride and sulphates.

FIGURE 19

Fractions of major nutrients in the soil



Compared with the daily nutrient requirement of high-yielding crops, the amounts of nutrients in the soil solution are very low and can only meet plant needs for a short period. This is especially true for phosphate and micronutrient cations. At high rates of nutrient uptake, the soil solution soon becomes depleted where it is not replenished from other fractions of available nutrients and unavailable forms, just as well-water is replenished by the groundwater resources as the water is drawn from the well (Figure 19). Adsorbed forms and other potentially available nutrient forms (the capability factor) continuously replenish the soil solution, which represents the intensity factor. Adequate fertilization ensures such replenishment. Where this cannot take place, nutrient deficiencies are very likely to occur.

Nutrients on the exchange complex

The fraction of exchangeable nutrients is much larger than their amount in the soil solution. In fertile soils of neutral soil reaction, about 75 percent of the adsorbed cations are of Ca and Mg and only 3–5 percent are of K. The adsorbed nutrients (cations of Ca, Mg, K, etc.) and anions, especially phosphate, are protected to a considerable extent against leaching loss and yet are easily available. An undesirable reality is that large amounts of nitrate are not adsorbed at all and, hence, can be easily lost through leaching.

Nutrients on the exchange complex must first be desorbed, exchanged or released into the surrounding soil solution before they can be taken up by plants. These replenish the soil solution. There is a steady exchange between nutrients on the exchange complex and those in the soil solution. A cation exchanges places with a cation and an anion can only exchange with another anion. Desorption dominates where the solution is diluted by nutrient uptake or addition of water, whereas adsorption dominates after input of water-soluble nutrient sources or with increasing dryness. Plant roots contribute to the release of adsorbed cations by the production of hydrogen ions (H^+), which may replace other exchangeable cations.

For some nutrients, the exchangeable fraction is a fairly good indicator of the total available pool of a nutrient in many soils. This is especially so in the case of K and Mg except for soils that can release significant amounts of non-exchangeable K during the crop season.

The inaccessible cations are those that are within the close-packed interior of clay mineral layers. These are regarded as fixed and mostly non-available. This is especially the case with nutrients such as K^+ and NH_4^+. K fixation in soils with certain clay minerals can result in severe K deficiencies. However, recent studies of several soils, specially the illite-dominant alluvial soils of India, indicate a very substantial contribution of non-exchangeable or "fixed" fraction of K to K uptake by crops (Subba Rao, Rupa and Srivastava, 2001). This calls for a change in thinking regarding the practical importance of non-exchangeable K for crop nutrition.

Moderately available nutrients

These nutrients are bound within different insoluble mineral and organic sources but are released during the cropping season. They can be easily mobilized by dissolving agents produced by micro-organisms or by plant roots. Some phosphate may be mobilized by organic acids and by mycorrhizae while some micronutrient cations by organic complexing agents known as chelates. The non-exchangeable K referred to above can also be considered in this category of moderately available nutrients.

It is difficult to distinguish this group from the much larger and partly similar pool of non-available nutrient sources as they are in a continuum. For example, typical P-containing compounds are calcium, aluminium and iron phosphates, but whether they belong to the moderately available nutrients depends on several factors. Moderately available P comes from freshly precipitated surface layers of amorphous material of small particle size, which facilitates their dissolution by dilute mineral and organic acids or by complexation. Examples of non-available forms of P are the occluded forms and tricalcium phosphates in alkaline soils. The same phosphates can become moderately available in a strongly acid soil. Insoluble iron phosphates can become available in reduced paddy soils where the ferric form becomes reduced to the soluble ferrous form of Fe.

Thus, the borderline between available and non-available nutrients in chemical compounds is arbitrary. Therefore, the amount of nutrients released into easily available forms during a cropping season is difficult to assess very accurately via practical approaches (discussed below).

Available versus actually used nutrients

Not all available nutrients in the soil are taken up by the roots even where there is a shortage. As root volume occupies only a small proportion of the soil volume and nutrients move relatively short distances to plant roots, they can only be utilized if they are within the reach of roots. Because of the small distances over which nutrients can move, many nutrients must be intercepted by growing plant roots. This is why physical conditions for root growth (soil structure) are very important and why plants with an extensive root system will generally be more efficient in nutrient uptake (discussed above).

The transport of most nutrients to the roots is mainly restricted to the small soil layer surrounding the roots (the rhizosphere). The mechanisms of transport valid for all nutrients, but to a different degrees, are:

- Mass flow: Nutrients flow passively with the water towards the root surface, a movement resulting from the active suction forces of the plant. Most of the nitrate and a part of other nutrients move this way.
- Diffusion: Here, nutrients move along a concentration gradient towards the root surface where the nutrient concentration is reduced because of uptake. Transport by diffusion is caused by random thermal agitation of the ions. Most of K, phosphate and micronutrient cations move by diffusion.

DYNAMICS OF PLANT NUTRIENTS IN SOILS

The content of available nutrients and their degree of availability and accessibility is not a static condition for all situations but ever-changing and very dynamic because of the various inorganic and biochemical processes that take place in soils. These depend on temperature, water content, soil reaction, nutrient uptake, input and losses, etc. Most forms of a nutrient (in solution, adsorbed, fixed, sparingly soluble, etc.) are in a dynamic equilibrium. External applications only cause temporary changes in the relation between different fractions, but the basic nature of the equilibrium remains intact over time.

An increasing water content (e.g. with rains or irrigation) causes a dilution of the soil solution (less nutrient per volume of water but with relatively more monovalent cations such as K^+), a stronger sorption of divalent cations and an increase in the mobilization rate. With increasing dryness, the soil solution becomes more concentrated and contains relatively more divalent cations (such as Ca^{2+}), but, most important, with dryness there is an increased immobilization of nutrients into only moderately available forms.

A decrease in pH from the neutral range results in a smaller proportion of exchangeable Ca and Mg. In the case of phosphate, there is initially a greater mobilization of calcium phosphate, but later a strong immobilization or even fixation into aluminium and iron phosphates. The availability of some micronutrients, especially of Fe, Mn and Zn, is increased strongly, and can even reach toxic levels. An increase in pH by liming can reverse the situation.

Nutrient uptake by plants, biological activity of soil organisms and external nutrient input can result in large or small fluctuations among the nutrient fractions, resulting in an ever-changing soil fertility status. To a certain extent, this can and should be controlled by appropriate management practices (Chapters 6 and 7). As a result of nutrient transformation and dynamics, when a nutrient ion reaches the root surface, the plant cannot distinguish whether this nutrient has come from soil reserves, mineral fertilizers or organic manures. In all probability it does not make any difference to crop nutrition.

DYNAMICS OF MAJOR NUTRIENTS

Nitrogen dynamics

The dynamics of N in soils are quite complex. These are depicted in many ways in the scientific literature. One example of N dynamics is provided in Figure 20.

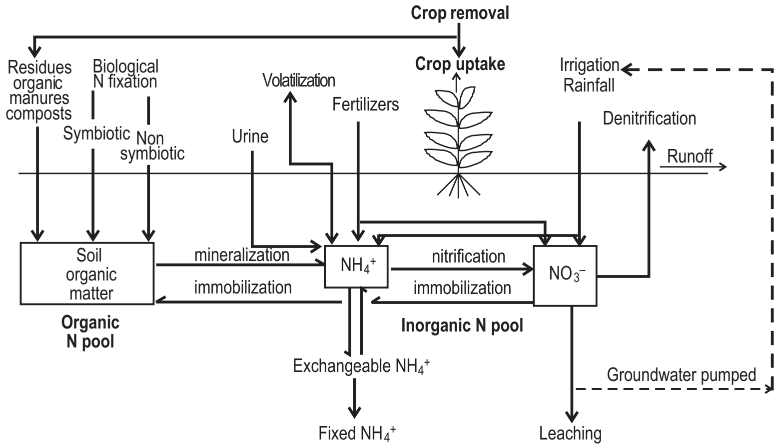
Many factors affect the level of plant available inorganic N. Soil N is primarily in the organic fraction. The N in the organic matter came initially from the atmosphere via plants and micro-organisms that have since decomposed and left resistant and semi-resistant organic compounds in the soil during development. As the bulk of the organic matter is in the upper horizons, most of the soil N is also in the topsoil.

Inorganic ionic forms of N (NO_3^- and NH_4^+) absorbed by roots usually constitute less than 5 percent of total soil N. In normal cropped soils, where ammonium is added through fertilizers or released from organic matter/organic manures/crop residues by mineralization, it is usually nitrified rapidly to nitrate. N added in the amide form (NH_2) as in urea is first hydrolysed to NH_4^+ with the help of urease enzyme. It can then be absorbed by roots as such or converted to nitrate and then absorbed. Where urea is left on the soil surface, particularly on alkaline soils, some of it can be lost through ammonia volatilization. Such ammonia can return to the soil with rain.

The ratio of NH_4^+ to NO_3^- in soil depends on the presence of satisfactory conditions for nitrification, which is inhibited by low soil pH and anaerobic

FIGURE 20

The nitrogen cycle



conditions. The nitrate thus formed can be absorbed by roots, immobilized by micro-organisms and become part of organic N, move down with percolating waters and leach out of the rootzone or be denitrified (lost) under anaerobic conditions. In cases where groundwaters are pumped for irrigation, the leached nitrate can re-enter the soil with irrigation water. Certain 2:1-type clays such as vermiculite and illite can fix ammonium ions in a non-exchangeable form.

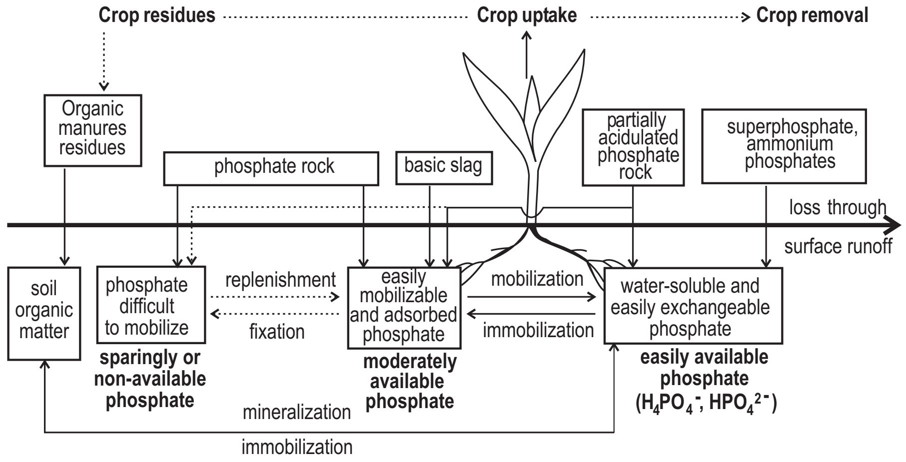
Gaseous forms of N include dinitrogen (N_2) from the atmosphere or denitrification or nitrous oxides (N_2O, NO) from denitrification. N in the soil atmosphere can only be used by symbiotic N-fixing bacteria such as *Rhizobium* or non-symbiotic N-fixing bacteria such as *Azotobacter, Azospirillum*, *Cyanobacteria* (blue green algae) and *Clostridium*. Several nitrogen gases that escape from the soil after denitrification or volatilization return to the soil with rain (precipitation). The nitrogen gas itself can return to the soil through biologically or industrially fixed N.

Phosphate dynamics

Chemically, P is one of the most reactive plant nutrient. Thermodynamic principles dictate that P compounds will tend to transform to less soluble and increasingly stable (and unavailable) forms with the passage of time. Hence, P is one of the most unavailable and immobile nutrient elements. One of the indicators of this is that barely 15–20 percent of the P added through fertilizer is recovered by the crop. It exists in the soil in a variety of forms. The dynamics of phosphate in soil present special problems because of the low solubility of most P compounds (Figure 21).

P added through soluble fertilizers first enters the soil solution, but much of it is converted into adsorbed P within a few hours. Very little of the added P stays

FIGURE 21
Phosphate dynamics in the soil

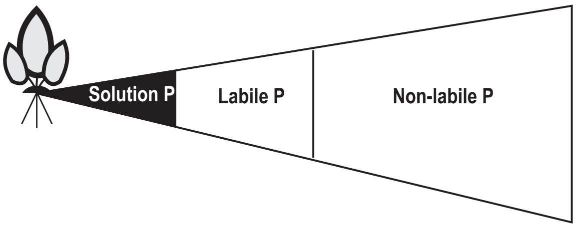


in the soil solution except in very sandy soils or soils lacking in the P-adsorbing agents (clays, oxides of Al or Fe, and carbonates of Ca or Mg). P added through PR is first solubilized by soil acids, after which it participates in various dynamic reactions as in case of soluble P.

Some important aspects of P dynamics are:

- Soil solution P: It is present in very small amounts and ranges from 0.01 to 0.50 mg/litre. In comparison, the concentrations of nutrients such as Ca, Mg and K are of the order of 400, 60 and 40 mg/litre, respectively. The relative distribution of anionic forms of P is dependent on soil pH. In the common pH range for soils, the dominant ionic form is $H_2PO_4^-$, which is also the most common form absorbed by plants. As the pH increases, the relative proportion of $H_2PO_4^-$ decreases while that of HPO_4^{2-} and PO_4^{3-} increases. In addition to ionic P in solution, some solution P may be present as soluble organic compounds, particularly in soils containing appreciable quantities of organic matter.
- Adsorbed P: In acid soils, the reactive phosphate ion is adsorbed onto the surfaces of iron and aluminium hydrous oxides, various clay minerals (e.g. illite and kaolinite) and aluminium–organic matter complexes. In neutral and alkaline soil, inorganic P may be adsorbed onto the microsurface of calcium and magnesium carbonates, iron and aluminium hydrous oxides, various clay minerals and calcium–organic matter complexes. Adsorbed P is a major source of P extracted by reagents used to estimate available P. It is in a dynamic equilibrium with solution P and replenishment as the P from solution is used up.
- Mineral P: These are mainly minerals of P combined with Ca, Al and Fe. In soils above pH 7, calcium and magnesium phosphate are dominant, while iron and aluminium phosphates are the dominant forms in acid soils. The amorphous forms can contribute to plant nutrition, but the crystalline forms are more stable and less reactive.
- Organic P: One-half or more of the total soil P may be present as organic P, the amount depending on the content and composition of organic matter. The major P-bearing organic compounds in soil are inositol phosphate, phospholipids, nucleic acids and others such as esters and proteins. The net release of this P to plants depends on the balance between mineralization and mobilization. The extent to which organic P is available to plants is not certain, but upon mineralization, it can enter the P cycle as adsorbed P.

FIGURE 22
Schematic representation of the three important soil P fractions for plant nutrition



- Available P: The replenishment of P into the soil solution following P uptake by plant roots is dependent on the quantity of P in the adsorbed and sparingly soluble mineral phase, as well as inorganic P in plant residues (Figure 22). Together, these constitute the reservoir of "readily available P" for soil solution replenishment. This is also known as labile P and is usually defined as the quantity of P that is in equilibrium with the soil solution during the life of the plant. The ability of a soil to maintain its P concentration in solution as plant roots absorb the P, or as P is added by fertilization, is known as the P-buffering capacity. The higher the buffering capacity is, the larger is the proportion of P in the solid phase relative to the solution phase.

Potassium dynamics

Among cations, K^+ is absorbed by plants in the largest amount. The four important forms of K in soil are: (i) mineral K; (ii) non-exchangeable K, or K fixed in between clay plates; (iii) exchangeable K; and (iv) K present in the soil solution. The abundance of different K fractions is usually as follows: 90–98 percent of total K is in mineral form, which is relatively (but not ultimately) inaccessible to a growing crop; 1–10 percent of total K is in the non-exchangeable (fixed) form, which is slowly available; and 1–2 percent of total K is in the exchangeable and water-soluble forms. Of this 1–2 percent, about 90 percent may be exchangeable and 10 percent in the soil solution. All these are in a dynamic equilibrium.

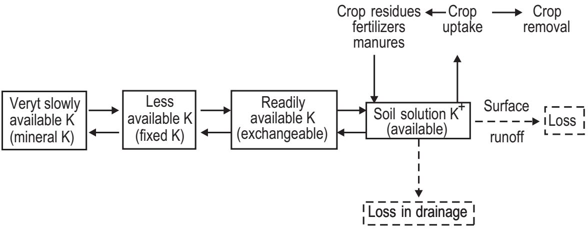
K dynamics are determined by the rate of K exchange from the clay and organic matter surfaces and the rate of release from soil minerals. Except for sandy soils, K^+ is stored on the surface of negatively charged clay minerals. This easily replaceable supply provides the soil solution with additional K when the soil-solution K concentration decreases as a result of crop uptake (Figure 23). Most traditional soil test measurements of available K include the exchangeable and the water-soluble fractions. There is increasing evidence that a part of the non-exchangeable fraction or fixed K should also be included in soil test measurements for making meaningful K fertilizer recommendations.

The K in common fertilizers (KCl, and K_2SO_4) is water soluble. On addition to the soil, the fertilizer dissolves in the soil water and dissociates into the cation (K^+) and the anion (Cl^- or SO_4^{2-}). The cation K^+ is largely held on to the exchange complex as an exchangeable cation and a small amount is present in a freely mobile form in the soil solution. Thus, the K added to soils can be transformed into three fractions apart from any incorporation into the organic matter.

In very sandy soils, particularly under high rainfall, K can also leach out of the rootzone. Similarly, a

FIGURE 23

Potassium dynamics in the soil



Potassium dynamics in the soil
Source: After A. E. Johnston (www. Kemira-growhow.com).

significant amount of available K can be added to the soil through crop residues, leaf fall and irrigation water in specific cases. Much of this K is soluble and can again be adsorbed on the exchange complex.

Calcium dynamics

The Ca content of different soils varies greatly, depending on the minerals from which the soils originate and on the degree of weathering. Ca content is lowest in acid peat soils and in highly weathered soils of the humid tropics where, owing to high acidity and heavy leaching losses, as little as 0.1–0.3 percent Ca may be left. On the other hand, calcareous soils sometimes contain more than 25 percent Ca, mostly in the form of calcium carbonate (FAO, 1992). In general terms, Ca in the soil occurs in the following forms:

- Ca-bearing minerals such as calcium aluminium silicates (e.g. plagioclase), calcium carbonates (calcite and dolomite), calcium phosphates (apatite), and calcium sulphate (gypsum);
- exchangeable Ca, adsorbed on negatively charged surfaces of organic and inorganic soil colloids as part of the CEC of the soil;.
- water-soluble Ca.

As is the case with other cations, the different forms of Ca in the soil are in a dynamic equilibrium. Plant roots take up Ca from the soil solution. When the Ca concentration (or activity) in the solution decreases, it is replenished by the exchangeable Ca. An exchange complex dominated by Ca and adequately provided with Mg and K is a favourable precondition for good crop yields. In humid temperate regions, the ratio of the nutrients is considered well-balanced when about 65 percent of CEC is saturated by Ca, 10 percent by Mg, 5 percent by K and the remaining 20 percent by others (H, Na, etc.).

Magnesium dynamics

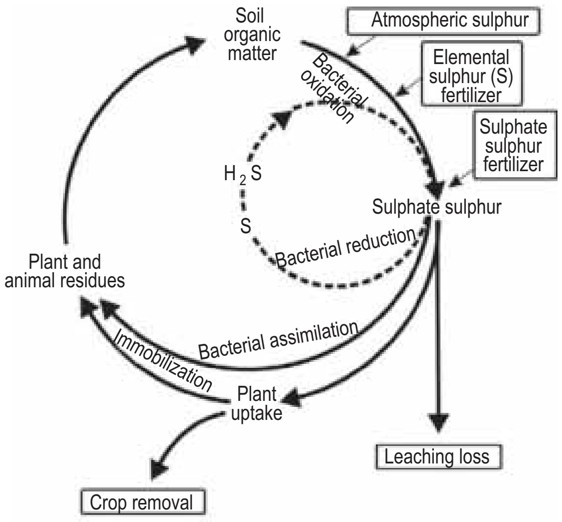
From the viewpoint of plant nutrition, the Mg fractions in the soil can be considered in a similar manner to those of K. Mg on the exchange complex and in the soil solution is most important for plant nutrition. Mg saturation of the CEC is usually lower than that of Ca and higher than that of K. The major forms of Mg are:

- non-exchangeable Mg (more than 90 percent of total Mg);
- exchangeable Mg (about 5 percent of total Mg);
- water-soluble Mg (about 1–10 percent of exchangeable Mg).

Non-exchangeable Mg is contained in the primary minerals such as hornblende or biotite, as well as in secondary clay minerals such as vermiculite, which hold Mg in their interlayer spaces. Non-exchangeable Mg is in equilibrium with the exchangeable Mg, which in turn replenishes the water-soluble or solution Mg. If the exchangeable Mg is depleted, as under exhaustive cropping, plants will utilize Mg from originally non-exchangeable sites at the clay minerals. However, its rate of release is too slow for optimal plant growth.

FIGURE 24

The sulphur cycle



Sulphur dynamics

The S content of soils is usually lower than that of Ca or Mg. It is in the range of milligrams per kilogram or parts per million rather than percent. In the soil, S occurs in organic and inorganic forms. A generalized picture of S dynamics is presented in Figure 24. In many soils, the organic S may be 75 percent or more of total S. Tropical soils generally contain less S than do soils in temperate regions because of their lower organic matter content and its rapid rate of decomposition. In a survey of S in the tropics, an average value of 106 mg/kg S for a wide range of tropical upland soils has been reported (Blair, 1979), which is well below the 200–500 mg/kg S reported for non-leached temperate soils in the United States of America.

In the soil, inorganic S exists mostly as sulphate. This is either readily soluble or adsorbed on soil colloids. In calcareous soils, sulphate may also be present as cocrystallized impurity with calcium carbonate (FAO, 1992). Some soils have gypsic horizons that are enriched with the sulphates of Ca and Mg. As plant roots take up S from the soil solution in the form of sulphate, only the soluble and the adsorbed SO_4^{2-} are readily available. In many soils, these fractions represent not more than 10 percent of the total S.

S present in SOM or S added through organic manures becomes available for plant use only after conversion to the sulphate form through mineralization. Conditions most favourable for the mineralization of organic S are: high temperatures (the optimum is around 40 °C); a soil moisture status that is about 60 percent of field capacity; conditions favourable for high microbial population; and a minimum S content of 0.15 percent in the organic matter.

When water-soluble sulphate fertilizers such as ammonium sulphate (AS) and single supersulphate are added, the sulphate enters soil water. From there, it can either be moderately adsorbed (stronger than chloride much weaker than phosphate) or immobilized in soil organic water after absorption by micro-organisms. A small portion remains in the form of sulphate ion in the soil solution. Where S is added in elemental or sulphide forms, as in pyrites, these undergo oxidation in the soil to furnish sulphate ions for plant use. This transformation is affected by soil pH, moisture status, aeration and particle size (fineness) of the S carrier.

Dynamics of micronutrients

Micronutrients in the soil are present in a number of forms and fractions (Katyal and Deb, 1982). In a general way, these can be described as follows:

- in the soil solution (soluble): immediately available;
- on the exchange complex (exchangeable): available pool, replenishes soil solution;
- adsorbed on soil surfaces and in inorganic compounds: available pool, replenishes soil solution;
- in organic matter and in living organisms: available on mineralization;
- in primary and secondary minerals: potential medium-long-term sources.

The nutrient ions in the soil solution are available immediately. As in the case of most nutrients, this very minute quantity by itself is unable to meet the total crop needs. It is in a dynamic equilibrium with the exchangeable and adsorbed forms, which sustain the soil solution and replenish it continuously as the nutrient are taken up by plants roots. The dynamics of individual micronutrients are outlined below:

Boron dynamics

The total B content of soils can range from 2 to 100 µg/g. Generally, coarse-textured soils contain less B than do fine-textured soils. Different forms of B in soils are water-soluble, hot-water-soluble, leachable and acid-soluble B. Adsorbed B plays a major part in determining the amount of B available for plant use. B adsorption is affected markedly by soil pH and is maximum at pH 8–9. B is also associated with organic matter, which on mineralization can furnish available B (Shorrocks, 1984).

Water-soluble B is concentrated mostly in the surface layers of well-drained soils. B is susceptible to leaching in coarse-textured soils and its movements in clay soils can be restricted severely. Liming reduces the availability of B, as is the case with several micronutrients except Mo. In saline sodic soils or fields irrigated with B-rich waters, the concentration of soluble B can reach toxic levels, which must be avoided.

Copper dynamics

The total Cu content of soils can vary from 2 to 300 µg/g with an average of 26 µg/g. The five pools of soil Cu are: soluble forms in the soil solution (usually very low concentration); stable organic complexes in the humus; Cu sorbed by hydrous oxides of Mn and Fe; Cu adsorbed on the clay–humus colloidal complex; and the crystal lattice-bound Cu in soil minerals, which is only released on weathering (Shorrocks and Alloway, 1988). Cu is complexed very strongly by organic matter. Cu in the soil solution is immediately available for plant uptake, and that in exchangeable form along with weakly complexed Cu is also quite labile.

The major factors controlling Cu dynamics are: soil pH, carbonate content, organic matter and clay content. The solubility of Cu decreases with an increase in soil pH, as following liming of acid soils. Both adsorption and complexation of Cu are strongest under alkaline conditions, and Cu deficiency is often more pronounced in such soils, although it is also encountered in acid soils.

Iron dynamics

Fe is the fourth most abundant element in the earth's crust, constituting about 5.6 percent. The total Fe content of soils can range from less than 1 percent to more than 25 percent. As is the case with most nutrients, total Fe in the soil is of little value in estimating the available Fe content. The various forms of Fe in soils are: immediately available Fe; the available pool including exchangeable Fe; Fe available on decomposition; and potential medium- to long-term sources (Katyal and Deb, 1982). An assessment of available Fe in soils remains a challenge.

In spite of high total Fe in soils, its adequate availability to crops is a major problem in many upland soils, particularly those of alkaline and calcareous nature. This is because crops take up Fe as Fe^{2+} while in upland soils Fe^{2+} is oxidized to the unavailable Fe^{3+} form. Soil pH is a major factor governing the solubility and availability of Fe to plants. In contrast with upland soils, the transformation in submerged soils is of greater significance for the Fe nutrition of rice. The concentration of Fe^{2+} increases upon reduction in flooded-rice soil. Decomposition of organic matter and green manures is also known to increase the pool of available Fe.

Manganese dynamics

The average content of Mn in soils is about 650 µg/g but it can range from a few to more than 10 000 µg/g (1 percent). Mn in soils is present in various forms: water soluble, exchangeable, easily reducible, complexed or organically bound, occluded within sesquioxides, and Mn present in crystalline minerals. Active or available Mn consists of the water-soluble, exchangeable and easily reducible fractions.

Available Mn constitutes 1–15 percent of the total soil Mn depending on climate conditions, soil type and the extraction method used. Bioavailability of Mn in soils depends upon:

- valence of Mn in the weathering solids;
- nature of the primary minerals;
- redox conditions (Eh and pH);
- organic complex formations;
- microbial activity;
- environmental factors and management practices.

Available soil Mn decreases with increases in soil pH and calcareousness.

Molybdenum dynamics

The average content of Mo in the soil surfaces is 1.5 µg/g, varying from traces to 12 µg/g. The molybdate ion (MoO_4^{2-}) is strongly adsorbed by soil minerals and colloids at pH less than 6. With extensive weathering, the secondary minerals formed may trap Mo. Hydrous aluminium silicate can also fix Mo strongly. Unlike other micronutrients, the availability of Mo increases with increases in soil pH.

Zinc dynamics

The total Zn content in normal soils can range from 10 to 1 000 µg/g. Highly weathered coarse-textured laterite and red soils are poor in Zn. In soil, Zn exists in several forms such as water soluble, exchangeable, complexed, organically bound and acid soluble. Where a fertilizer such as zinc sulphate is added to soils, its Zn dissolves in water and enters one or more of these fractions. Zn present in water-soluble, exchangeable and complexed forms can be considered as available to plants.

Plant available Zn is usually less than 1 percent of total soil Zn. The organic-matter-bound Zn decreases with increase in pH regardless of soil texture. Soil submergence also reduces Zn availability, which is linked with changes in pH and formation of certain relatively insoluble products of Zn. Overliming acid soils can reduce Zn availability drastically and result in its severe deficiency (Gupta, 1995).

ASSESSMENT OF AVAILABLE NUTRIENT STATUS OF SOILS AND PLANTS

The evaluation or assessment of soil fertility is perhaps the most basic decision-making tool for balanced and efficient nutrient management. It consists of estimating the available nutrient status of a soil for crop production. A correct assessment of the available nutrient status before planting a crop helps in taking appropriate measures for ensuring adequate nutrient supply for a good crop over and above the amounts that the soil can furnish. The techniques used include soil testing and plant analysis, the latter including related tools such as total analysis of the selected plant part, tissue testing, crop logging and the diagnosis and recommendation integrated system (DRIS), as described below. The objective of all these techniques is to assess the available nutrient status of soils and plants so that corrective measures can be taken to ensure optimal plant nutrition and minimum depletion of soil fertility.

Soil testing

Soil testing is the most widely used research tool for making balanced and profit-maximizing fertilizer recommendations, particularly for field crops. Soil testing can be defined as an acceptably accurate and rapid soil chemical analysis for assessing available nutrient status for making fertilizer recommendations. Soil testing as a diagnostic tool is useful only when the interpretation of test results is based on correlation with crop response and economic considerations to arrive at practically usable fertilizer recommendations for a given soil–crop situation.

The amount of a nutrient estimated as available through soil testing need not be a quantitative measurement of the total available pool of a nutrient but a proportion of it that is correlated significantly to crop response. Soil testing does not measure soil fertility as a single entity but the available status of each nutrient of interest is to be determined. Based on a high degree of correlation between the soil test value of a nutrient and the crop response to its application, the probability of a response to nutrient input can be predicted. This serves as a basis for making practical fertilizer recommendations, which should be adjusted for nutrient additions expected to be made through BNF and organic manures. Soil testing has to be done for each individual field and for each nutrient of interest. It may be repeated every 3–4 years.

The major steps in practical soil testing for a relatively uniform field of up to 1 ha are:

- representative soil sampling of the fields;
- proper identification and labelling of the sample;
- preparation of soil sample;
- extraction of available nutrients by an appropriate laboratory method;
- chemical determination of extracted nutrients;
- interpretation of soil analysis data – soil test crop response correlation is the key issue.

The usefulness of soil testing depends on a number of factors, such as representative and correct soil sampling, analysis of the sample using a validated procedure, and correct interpretation of the analytical data for making practical recommendations. A sound soil testing programme requires an enormous amount of background research on a continuing basis to cater to changing needs such as the development of new crop varieties, better products and agronomic practices. Such research also helps to determine:

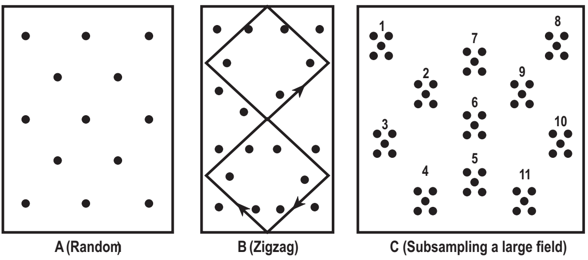
- the chemical forms of available nutrients in soils and their mobility;
- the most suitable extractants for accurately and rapidly measuring such forms;
- the general health and productivity of the soils for various crops;
- norms for field soil sampling and sample processing techniques;
- the response of crops to rates and methods of fertilizer application;
- the effect of season on nutrient availability;
- interactions of a nutrient with moisture and other nutrients.

Soil sampling and sample preparation

The quality of soil testing depends largely on reliable sampling, otherwise the results, even if analytically accurate, are worthless. The test sample (which is only about 0.00001 percent of the topsoil weight) must be representative for the field or the part of the field being tested. Figure 25 provides the suggested sampling procedure for a small field (Finck, 1992) and for a large field (Peck and Melsted, 1967). The best time for sampling is before sowing or planting and certainly

FIGURE 25

Representative soil sampling for small and large fields



A (Random) B (Zigzag) C (Subsampling a large field)

Note: A and B are for fields of up to 1 ha; C is a recommended sampling plan for a field of about 15–16 ha with each spot indicating the site of a subsample.
Sources: Finck, 1992; Peck and Melsted, 1967.

before fertilizer application. Each sample should have an information sheet with field identification, farmer's name and address, previous crops, the crop for which nutrient recommendation is sought, availability of irrigation, and previous fertilization, etc.

A soil sample should cover identifiable soil areas within a field. Abnormal soil patches, areas near a fence or used for storing animal manure or crop residues should be disregarded or sampled separately. For soil sampling, special augers with a core diameter of 1–2 cm are convenient, but small spades can also be used. In any case, a uniform slice of soil should be taken from top to bottom of the desired sampling depth. About 20 cores are taken from a field of 1 ha. Sampling depth can be 20–30 cm on arable land from the plough layer and 0–10 cm on grassland. For better interpretation, a few samples from deeper soil layers should be taken.

The individual cores or slices are then collected in clean containers and mixed well. From this, a final sample of about 0.5 kg is drawn for analysis. The moist samples should be air dried as soon as possible and sieved. Only the fine soil (less than 2 mm) is used for analysis. Most soil sampling is still done by hand, but special sampling machines have been developed in order to facilitate this on large areas. As large fields often have large variations in soil type, they must be divided into subunits of different soils.

Analysis for available nutrients

The concentrations of nutrient in the extracted solutions are determined by standard methods; the results are expressed as nutrient concentrations of air dry soil, using standard units: percent or g/kg or mg/100 g or mg/kg = μg/g = ppm; for organic soils, g/litre of soil are used. Nutrients may be indicated as oxides, e.g. K_2O, or as elements, e.g. K, but it must be stated very clearly whether oxide or elemental

TABLE 12

General soil test limits used for classifying soils into different fertility classes

Nutrient	Method/extractant	General fertility class*		
		Low	Medium	High
N (% organic C)	Organic carbon	< 0.5	0.5–0.75	> 0.75
N (kg/ha)	Alkaline permanganate	< 280	280–560	> 560
P_2O_5 (kg/ha)	Sodium bicarbonate	< 23	23–56	> 56
K_2O (kg/ha)	Ammonium acetate	< 130	130–335	> 335
S (kg/ha)	Heat soluble, $CaCl_2$	< 20	20–40	> 40
Ca (% of CEC)	Ammonium acetate	< 25		
Mg (% of CEC)	Ammonium acetate	< 4		
Zn (μg/g)	DTPA	< 0.6	0.6–1.2	> 1.2
Mn (μg/g)	DTPA	< 3.0		
Cu (μg/g)	DTPA/ammonium acetate	< 0.2		
Fe (μg/g)	DTPA	< 2.5–4.5		
Fe (μg/g)	Ammonium acetate	< 2.0		
B (μg/g)	Hot water	< 0.5		
Mo (μg/g)	Ammonium oxalate	< 0.2		

* Very general limits based on several published Indian sources (Tandon, 2004).

forms are used in order to avoid confusion and errors. For example, 1 unit of P becomes 2.29 units of P_2O_5, and 1 unit of K becomes 1.2 units of K_2O.

The choice of a suitable extractant for available nutrients is very important because of the different amounts of nutrient measured and the degree of their correlation with crop response. Most soil testing methods are based on chemical extractants, as summarized above and listed in Table 12.

For N, the water-soluble fraction (nitrate) is most suitable but the capacity to mobilize organic N can provide additional information. For the nutrient cations (Ca, K and Mg), the exchangeable portion is representative of the whole available fraction in most case and, therefore, determined by suitable extractants such as ammonium acetate and barium chloride. In soils that can release non-exchangeable K, a measurement of exchangeable fractions only does not provide a complete picture.

For phosphate, the choice is more difficult as soil reaction influences the solubility of P. A typical standard method for more acid soils is Bray and Kurtz extractant No. 1 popularly known as the P_1 test (0.03 N NH_4F + 0.025 N^- HCl), whereas for neutral and alkaline soils the Olsen method (0.5 N Na bicarbonate solution of pH 8.5) is more suitable. Among the major nutrients, the soil test methods for P are relatively more reliable.

For most micronutrient cations, diethylenetriamine pentaacetic acid (DTPA) is now widely used as an extractant. In the case of anions, the most commonly used extractant is hot water for B, and Grigg's reagent (ammonium oxalate of pH 3) for Mo.

Although a wide variety of extractants are used, most countries use standard extraction procedures, calibrated for specific soil and climate conditions in order to generate locally applicable recommendations. Soil testing needs to be simple, cheap and relevant to local conditions.

In addition to standard soil testing, simple kits are also available for use by farmers or advisers in the field with immediate but rather doubtful results. There is no good substitute for a valid soil test supplemented by appropriate plant analysis information. As a diagnostic tool, particularly for N in standing crops, the leaf colour chart (LCC) is finding use in rice, maize and some other crops.

Interpretation of analytical data for fertilizer requirement

After soil analysis, the concentrations of available nutrients measured must be interpreted into ranges of nutrient supply and then into the nutrient amounts required to reach a certain yield level. In general, the lower the soil fertility status (soil test value) is, the greater is the need for external nutrient application. For example, a very low soil test indicates a large deficiency of the nutrient in question and, accordingly, a large amount of external application to correct that deficiency and supply adequate amount of nutrient for optimal yield. Similarly, a very high soil test value indicates surplus nutrient supply, hence, no external addition of the nutrient is usually needed. In some agriculturally advanced regions, even on P-rich soils, P application is recommended to compensate for crop removals so that soil fertility is not depleted. Many farmers in developing countries cannot afford to follow such a strategy.

TABLE 13

Interpretation of soil test data for some nutrients in soils with medium CEC

	Available (extractable) nutrients			Expected relative yield without fertilizer
	P	K	Mg	
Soil fertility class	**(mg/kg soil)**			**(%)**
Very low	< 5	< 50	< 20	< 50
Low	5–9	50–100	20–40	50–80
Medium	10–17	100–175	40–80	80–100
High	18–25	175–300	80–180	100
Very high	> 25	> 300	> 180	100

Source: FAO, 1980.

For macronutrients, the data are generally classified into categories of supply, e.g.: very low, low, medium, high, very high. From these categories, the nutrient amounts required for an optimal or stated yield level are estimated. For micronutrients, a critical level is generally used to decide whether an application of that nutrient is needed. Table 13 provides a generalized idea of the relation of available nutrient status to expected yields (without external addition) for a soil of medium CEC (10–20 cmol/kg). The values in the final column of the table indicate the approximate yield level that the existing soil fertility level could support.

In most cases, soil nutrient status is stated as low, medium or high. This needs to be done for each nutrient. For nutrients other than N, P and K, a single critical level is usually designated below which a soil is considered to be deficient in that nutrient, hence requiring its application. As an example, the most commonly used methods and values employed for delineating soils according to their available nutrient status have been provided in Table 12 for India, where more than 500 soil testing laboratories have been established. Most of these laboratories test soil samples for texture, pH and status of available N, P and K. These figures represent general norms but can vary widely with the type of soil, crop and method used. Therefore, only locally developed fertility limits should be used for specific soils and crops, even within a country or region.

On the basis of soil testing, nutrient supply maps can be drawn for farms, larger regions and countries. Such maps provide a useful generalized picture of the soil fertility of an area. However, the extent to which soil fertility maps can be used for planning nutrient management strategies depends on how thorough, recent and representative the soil sampling has been on which such maps are based. Macrolevel maps are more useful as an awareness and educational tool rather than for determining out nutrient application strategies.

Plant diagnosis

The nutrient status of plants can by assessed on a qualitative basis by visual observation and, more accurately, on a quantitative basis by analysing the mineral composition of specific parts of growing plants.

Visual plant diagnosis

A healthy dark-green colour of the leaf is a common indicator of good nutrient supply and plant health. The degree of “greenness” can be specified in exact terms for each crop using Munsell's Plant Colour Chart or other such charts. Any change to light green or a yellowish colour generally suggests a nutrient deficiency where other factors are not responsible such as cold weather, plant diseases and damage caused by sprayings, air pollution, etc.

A deviation from the normal green colour is easily detected. However, it is by no means always caused by N deficiency, as usually assumed. For example, it is a common but questionable practice to always relate light-green late foliar discolouring with N deficiency, but it can often be caused by other deficiencies. Even where the colour is more or less "satisfactory", there may be a latent deficiency ("hidden hunger") that is often difficult to establish from visual observation but can still cause yield reduction. It usually requires chemical plant analysis for conformation.

Fully developed deficiency symptoms can be a useful means for detecting nutrient deficiencies. However, they are only reliable where a single nutrient and no other factors are limiting. Chapter 3 has covered deficiency symptoms by nutrient. However, some general guidelines for the appearance of nutrient deficiencies in cereals are:

- ➢ Deficiencies indicated by symptoms appearing first on older leaves:
  - chlorosis starting from leaf tips, later leaves turn yellowish-brown: N;
  - reddish discoloration on green leaves or stalks: P;
  - leaves with brown necrotic margins, wilted appearance of plant: K;
  - stripe chlorosis, mainly between veins, while veins remain green: Mg;
  - spot necrosis: greyish-brown stripe-form spots in oats (grey-speck disease): Mn;
  - dark-brown spots in oats and barley, whitish spots in rye and wheat: Mn.
- ➢ Deficiencies indicated by symptoms appearing first on younger leaves:
  - completely yellowish-green leaves with yellowish veins: S;
  - yellow or pale yellow to white leaves with green veins: Fe;
  - youngest leaf with white, withered and twisted tip (oats and barley). Cu;
  - yellowish leaves with brownish spots (part of acidity syndrome): Ca.

Chlorosis refers to a condition in which the leaves appear with a light green-yellowish tinge, but the tissue is still largely intact. Necrosis means a brownish dark colour with irreversibly destroyed tissue. The easiest way of visually diagnosing nutrient deficiency symptoms is their identification with good-quality colour photographs of the specific crops. Even with these, farmers are advised to seek professional help and plant analysis as needed before taking corrective measures.

Plant analysis

The nutrient concentration of growing plants provides reliable information on their nutritional status in most cases, expect in the case of Fe. It reflects the current state of nutrient supply and permits conclusions as to whether a supplementary nutrient application is required. Plant analysis generally provides more current plant-based information than soil testing but it is more costly and requires greater efforts in sampling, sample handling and analysis. Ideally, both tools should be used as they complement each other. The key features of plant analysis are:

- Sampling: Representative sampling should be done of specific plant parts at a growth stage that is most closely associated with critical values as provided by research data. Sampling criteria and the procedure for individual samples is similar to that for soil testing in that it should be representative of the field. The composite sample should be about 200–500 g fresh weight.
- Sample preparation: The collected sample should be washed as soon as possible first with clean water and then with distilled water. It should be air dried followed by oven drying at 70 °C. Finally, it has to be carefully ground, avoiding contamination, and the powder mixed well.
- Analysis: After dry or wet ashing and complete dissolution, the determination of nutrients by standard analytical methods is carried out. The results are expressed as a concentration on a dry-matter basis (percent or mg/g for major nutrients; µg/g = mg/kg = ppm for micronutrients).
- Interpretation: Interpretation of plant analysis data is usually based on the total concentrations of nutrients in the dry matter of leaves or other suitable plant parts, which are compared with standard values of "critical nutrient concentrations" ("critical values") and grouped into supply classes. This will determine whether immediate action such as foliar spraying is needed to correct a deficiency. Conclusions can also be drawn on whether the amount of fertilizer applied at sowing time was sufficient or should be increased for the next crop. Where the concentration is in the toxicity range, special countermeasures are required but no application is needed.

For some nutrients, such as Ca and Fe, the "active" (mobile) nutrient content of plants should be considered because immobilization can make the total concentrations misleading. The nutrient concentrations of green (fresh) material or of plant sap can be used as a suitable basis for interpretation in some situations. Because of many interactions between nutrients and other inputs, more sophisticated indicators than just individual concentrations have been suggested, such as simple or complex nutrient ratios, e.g. the DRIS method (discussed below).

Critical values

Between the nutrient concentrations of the deficiency range and those of adequate supply, there is the critical nutrient range as described in Figure 11. The critical level is that level of concentration of a nutrient in the plant that is likely to result in 90 percent of the maximum yields. The plant nutrient concentrations required depend on the cultivar and expected yield level. Standard tables of plant analysis interpretation are based on requirement levels for very high yields (maximum yield) or on those for the more practical and realistic medium to high yields corresponding to critical values of 90 percent.

The main advantage of critical values, once properly established, is their wide applicability for the same crop. Their disadvantage is that they only provide a yes or no type of information and do not cover the entire range over which nutrient supplies need to be managed. Table 14 presents some critical data for a range of crops based on various sources. In most cases, these correspond to 90 percent of maximum yield but in some cases to maximum yield. These are approximations compiled from various sources. Specific situations require further refinement. For example, critical concentrations in the case of oil-palm are different for young palms and for older palms (Fairhurst and Hardter, 2003). A selection of critical plant nutrient concentrations for many crops has been compiled by the International Fertilizer Industry Association (IFA, 1992) among others.

TABLE 14

Critical nutrient concentrations for 90-percent yield for interpretation of plant analysis data

Element	Wheat & rice	Oilseed rape	Sugar cane	Alfalfa (Lucerne)	Grass[*]	Citrus
			(%)			
N	3.00	3.50	1.50	3.50	3.00	2.50
P	0.25	0.30	0.20	0.25	0.40	0.15
K	2.50	2.50	1.50	2.00	2.50	1.00
Mg	0.15	0.20	0.12	0.25	0.20	0.20
S	0.15	0.50	0.15	0.30	0.20	0.15
						(µg/g)
Mn	30.0	30.0	20.0	30.0	60.0	25.0
Zn	20.0	20.0	15.0	15.0	50.0	20.0
Cu	5.0	5.0	3.0	5.0	8.0	5.0
B	6.0	25.0	1.5	25.0	6.0	25.0
Mo	0.3	0.3	0.1	0.2	0.3	0.2

Note:

Growth stage and plant parts used: wheat/rice: 1–2 nodes, whole shoots; oilseed/rape: pre-flowering, youngest mature leaf; sugar cane: 5–7 months, third leaf blade from top; alfalfa (Lucerne): pre-flowering, whole shoots; grass: pre-flowering, whole shoots; citrus: 5–7 months old leaves from mid of non-fruiting branch.

[*] Not critical but optimal concentrations for cows producing 15 litres of milk per day.

Field experiment

This is a proven and effective method for assessing nutrient needs. It is also essential for the calibration of soil test and plant analysis results with crop response. Fertilizer experiments provide direct information on the amounts of nutrients required for a crop in a specific environment at a given yield level. However, because of the considerable expertise, effort and cost involved, they are not suitable for individual farmers. These are used mainly by researchers for generating background data needed for making practical recommendations for farmers.

Fertilizer experiments are required to reach conclusions on soil nutrient supply, on optimal rates and combinations of nutrients, best timing, application techniques, etc. The experiments are usually carried out under field conditions both at research stations and on the fields of cooperating farmers. Greenhouse experiments are less expensive but provide only limited information of practical value. Field experiments can be simple test plots or complex replicated trials.

Control test plot

This is the simplest field experiment (e.g. strip technique) where a small plot in the field is treated differently from the main field. For a farmer new to fertilizer use, the strip can be used to demonstrate the need for fertilizer. In this case, the strip receives optimal balanced fertilizer and the remaining field is unfertilized or treated as per the farmer’s normal practice. The technique can be used also to determine whether a particular nutrient is likely to be deficient and should be included in the fertilizer programme. For example, to determine the need for S, the strip is fertilized with NPK + S while the remaining area receives NPK. By comparing the colour, growth and yield of the crop in the selected strip and the remaining field, a conclusion can be made about the changes required in existing fertilization practices. This can be quite convincing as it is carried out on the farm. However, adequate supervision is needed in order to ensure that the selected strip is not disturbed. This technique serves the purpose of a simple experiment as well as an on-farm demonstration.

Complex experiments

The design and scope of field experiments varies from simple studies of nutrient needs (e.g. whether crops respond to N, P or K), to increasing nutrient rates for determining the optimal rate and, finally, to complex experiments with several nutrients and other factors. For successful experiments, a number of rules have to be observed. Prerequisites for good field experiments are:

- The experimental field should have a uniform soil, minimum variations and a statistically designed layout.
- The layout of the experiment can range from simple blocks in a single row to more complicated multivariate designs such as Latin square in order to better eliminate soil variation. The total area of an experiment is usually limited by practical management considerations.
- The number of replications required depends on the purpose of the experiment (normally, four replications are required for statistical analysis).
- The size of plots depends largely on the area available and the crop in question. For small cereals, plots of about 20–25 m^2 may be sufficient, whereas larger plots are required for wide row crops such as oilseed rape, sugarcane, tobacco or maize.
- Rates of nutrient application should preferably be graded into equal steps from zero (control plot) to the maximum yield (or above), e.g. 0–50–100–150. A larger number of smaller steps or increments give more information but costs more.
- The total number of plots is determined by the number of different treatments and the number of replications, e.g. five rates of N application (say, 0–40–80–120–160 kg/ha) with four replications requires 20 plots. With three nutrients (say, N, P and K), each with three rates of application, there will be 27 combinations, and with four replications, the experiment will need 108 plots. If this number is too large, it can be reduced to about ten important combinations, such as $N_0P_0K_0$, $N_1P_1K_1$, $N_2P_1K_1$, $N_2P_2K_2$, etc.
- Good management practices including effective measures for weed control and crop protection must be followed in order to guarantee good crop growth.
- Special attention should be given to the control plot (plot without the test fertilizer or nutrient) as this determines the base production level. Occasionally, the test fertilizer or nutrient is added to the control plots

rendering the whole experiment useless, especially if there are no replications. This is more often the case where experiments are conducted on the fields of farmers.

- The results must be analysed by appropriate statistical methods, e.g. analysis of variance, and expressed in a manner indicating the statistical significance of differences in yield or composition. Statistical significance of experimental results does not imply automatically that they are true in a scientific sense. Where significance contradicts common experience, a plausibility check is required because all kinds of mistakes may occur in field experiments.
- Such field experiments usually have to run for at least three years in order to obtain valid conclusions and eliminate season-to-season variations.

The interpretation of field experiments is a standard procedure using statistical methods, and the results are directly applicable. The extrapolation of experimental results requires special care. They are strictly valid only for the crop grown, for the annual growth conditions (unless from long-term experiments), for the soil area of the experimental plot, etc. However, they can often be extrapolated to the surrounding area or similar growth conditions elsewhere through modelling.

IMPACT OF SOIL FERTILITY ON CROP PRODUCTIVITY

The basic aim of sound soil fertility management is to enhance crop productivity, to sustain it, and to keep the soils in good health – physically, chemically and biologically.

Improving soil fertility – the foundation of high-input cropping

The high yield levels obtained are a result of suitable crop growth conditions, optimal and balanced nutrient management (keeping in view the initial soil fertility) and adoption of best management practices. When taken year after year, such steps lead to an improvement in soil fertility, which makes the production of high yields sustainable. After more than a century of mineral fertilization, along with organic supplements available to the farmers, there has been a considerable increase in organic and mineral contents of major nutrients (N, P and K) in the soil in many parts of the world. At the same time, in large areas, soils continue to be mined of their nutrient reserves and are becoming depleted. Such soils are losing their ability to sustain high levels of crop productivity and safeguard food security.

Because of improved soil fertility, cereal yields on many highly productive soils remains high for some time even where left unfertilized. They may remain at 8–10 tonnes/ha in the first year, decrease to 5–7 tonnes/ha after some years, and further to about 3–4 tonnes/ha. Finally, after a longer unknown period, they can probably decline to 1–3 tonnes/ha. Wherever high yields are to be obtained on a sustained basis, the crop requires access to adequate amounts of all essential plant nutrients. Wherever the fertility of a soil is unable to furnish such amounts, soil fertility has to be improved through external additions of required plant nutrients. This is best accomplished through INM.

Degradation and improvement of soil fertility

Soil degradation leads to a deterioration in soil quality, resulting in yield decline. Soil degradation lowers the actual or potential soil productivity in different ways:

- loss of the fertile topsoil components through erosion by water and wind;
- physical degradation (poor structure, compaction, crusting and waterlogging);
- chemical and biological degradation, e.g. decrease in organic matter and soil bioactivity, loss of nutrients through various routes, soil acidification or salinization with their accompanying problems of nutrient deficiencies, toxicities and imbalances.

Soil degradation is widespread in many parts of the world. The basic causes of soil degradation are the result of human activities such as deforestation, overgrazing and poor soil management. Factors that cause soil degradation are interrelated. About 1 200 million ha worldwide are considered to be affected by soil degradation, mostly by erosion. It has been estimated that human-induced soil degradation has affected 46 million ha in Africa and 15 million ha in Asia (FAO, 2000a). Out of these, 25 percent of such soils in Africa and 67 percent in Asia are moderately to severely affected.

Degradation of soil fertility

Soil fertility is not a stable property but a dynamic one. There are widespread problems of soil fertility degradation under many cropping systems even on soils with good initial soil fertility. The result of such a decline is a reduced nutrient supply, which reduces crop yields.

From plant nutrition considerations, chemical degradation of the soil, particularly its fertility status, is of greatest concern. Losses of nutrients from soil can be caused by soil erosion, leaching, crop removal or in the form of gases (as in case of N and to a lesser extent S). Nutrient removal by crop products compared with external nutrient inputs can be similar, higher or lower. Negative nutrient balances result where nutrient removals exceed nutrient additions. These are a cause of soil fertility depletion or nutrient mining. Positive nutrient balances indicate a buildup or improvement in soil fertility.

Nutrient mining or depletion is a widespread problem in low- and medium-input agriculture. This is a major threat to productive sustainable farming. It is accelerated by imbalanced fertilization. Nutrient mining can cause the exhaustion of any nutrient required in moderate to large amounts. It can be particularly severe in the case of N, P, K and S depending on soil nutrient reserves and the amounts replenished. A negative balance can be acceptable for a short period, but, where prolonged, it will lead to soil deterioration. It is expensive to improve depleted soils.

Experience from Africa shows that, on poor soils, 33 percent of the total soil N may be lost within 10 years and 33 percent of P within 20 years, even at grain yields of 2 tonnes/ha. In comparison, K losses are relatively smaller and those of

Zn are very small. In Africa, several countries have a negative nutrient balance of more than 60 kg of total nutrients annually (FAO, 2000a). Negative nutrient balances are quite common also in many Asian countries. For example, in India, the annual gap between nutrients removed by crops and those added through fertilizers has been in the range of 8–10 million tonnes of $N + P_2O_5 + K_2O$ for several years (Tandon, 2004).

Improving soil fertility

In many situations, soil degradation can be reversed by required inputs and improved management. However, once the topsoil has been lost, the damage has been done and there is little or no possibility of restoring it. Loss of topsoils is one of the worst forms of soil degradation. Some generally suggested measures for improving soil fertility/productivity are:

- ➢ Physical factors:
  - shallow main rooting zone (deeper cultivation where possible);
  - hard layers in subsoil (mechanical destruction of such layers);
  - very sandy soil (use of organic manure on priority);
  - poor structure (addition of organic matter, mulches, amendments).
- ➢ Chemical factors:
  - strong acidity (application of limestone, avoiding acid-forming fertilizers);
  - strong alkalinity (apply amendments such as gypsum and pyrites, green manuring);
  - strong salinity (leaching with non-saline water, growing salt-tolerant crops, green manuring);
  - nutrient toxicities (use of suitable amendments, drainage, tolerant crops);
  - low nutrient status (application of deficient nutrients through mineral, organic and biological sources);
  - nutrient fixation (application of suitable amendments, placement of fertilizers).
- ➢ Biological factors:
  - low organic matter (application of organic manures, compost, green manure);
  - poor microbial activity (improvement of aeration, drainage, correction of pH, organic inputs).

Even under conditions of low input cropping and with nutrient depleted soils, fertility degradation can be reversed in acid soils. The first step should be a better P supply with phosphate fertilizers, possibly with some lime application and N input via N fixation by legumes, resulting in a spiralling upwards process.

While soil improvements may result in 50 percent higher yields at a low-input level, more impressive results can be obtained at a high-input level. A good example is that of the formerly degraded and low-yielding, but now highly productive soils of Western Europe with present wheat yields of 8–10 tonnes/ha. The original cereal yield ranged from 0.5 to 1.5 tonnes/ha, a yield that can still be observed in unfertilized control plots of old field experiments and on the fields of millions of farmers in many parts of Asia, Africa and Latin America.

FERTILITY MANAGEMENT OF SOILS IN DIFFERENT CLIMATE REGIONS

The wide range of soils provides vastly different situations for the application of fertilizers and other sources of plant nutrients. The better the fertility of a soil is understood, the more correctly it is possible to develop and adopt nutrient management strategies. Only very few soils are ideal for plant growth by nature and supply nutrients in adequate amounts for high yields. In fact, most soils are in the wide medium-fertility range and many must be considered as poor. There may be many soils with high natural fertility, but in practical agriculture, these must be seen in the context of specific requirements of the crops to produce high yields. From a practical point view, most soils can be considered as requiring some degree of intervention and amelioration.

Soils of the temperate regions

The discussion here is restricted to the Podzolic and transitional soils as these are the main types on sandy substrates. These are predominantly former forest soils and cover large areas. Their organic matter content may be low or high, but the humus forms are generally poor in N and have undesirably high C:N ratios. These soils benefit from organic manures and mulch applied to improve their WHC and nutrient supply. Their fertility ranges from low to medium and their natural yield potential is often low. However, in humid rainy climates, improvement in their nutrient status offers considerable possibilities for yield increases.

On many Podzols, the initial amelioration required consists of removal of root-impeding conditions and better drainage. The often very high soil acidity and damage caused by it must be reduced or overcome by liming. This brings about several improvements, ranging from increase in activity of soil organisms to improvement of nutrient supply. Sandy soils are very sensitive to overliming and the optimal soil reaction (pH 6) is often exceeded. Higher pH values often cause secondary problems, of which Mn deficiency is the most frequent.

The general low status of nutrients, especially in sandy Podzols requires relatively high application of N, P and K. Because of their low nutrient storage capacity, split applications of N are beneficial (to reduce leaching). Because of the low pH, easily mobilized phosphate forms are generally more suitable than water-soluble ones. As Mg deficiency is common on these soils, liming materials containing Mg such as dolomite should be used. Deficiencies of micronutrients are also common. The deficiencies of Mn and B are frequently caused by high pH. Cu deficiency is characteristic of partly boggy sandy soils that have Cu-fixing humus forms. For the health of grazing animals, Cu and Co deficiencies need to be corrected.

Climate-stress factors that need to be taken into account are cold spells in spring, which primarily damage poorly nourished young plants, and dry periods in spring, which increase nutrient immobilization. Thus, full utilization of the production potential of these soils requires a comprehensive plant nutrient management programme with relatively large inputs, which offers large possibilities for yield increases.

Soils of the humid tropical regions

Red loam and red earth soils

Red loams and red earth soils (Latosols, Ferralsols, etc.) cover large areas on both sides of the equator under tropical rain forests and moist savannahs. Their average fertility ranges from low to medium, except for some red earths that have especially high fertility. Even where these soils support abundant natural vegetation, crop yields are frequently low. However, there are considerable possibilities for yield improvement. The introduction of intensive high-yielding production systems is possible because of favourable climate conditions. Sustainability of such systems in these soils can be achieved by using lime and a nutrient management programme that addresses the problems caused by production-limiting soil properties and the humid tropical climate.

Common properties of humid tropical soils relevant to nutrient supply and crop nutrition are:

- limited usable soil depth owing to hard layers (iron oxide concretions, stone layers);
- low natural soil reaction, often between pH 4 and 5, resulting in deficiencies of P, K and Mg and in Al toxicity;
- low nutrient reserves in old mineral soils (partly compensated by a higher mobilization rate than in temperate regions), in organic soils, the contents of P, K and Mg are often very low;
- low humus and N content and a rapid mineralization of organic matter under warm and more or less permanent moist conditions;
- low CEC of kaolinitic clay minerals in these soils is responsible for high losses of K, Ca and Mg by leaching under high rainfall in annual cropping;
- strong adsorption (fixation) of P on some soils with high contents of active iron and aluminium oxides;
- stable soil structure tends to deteriorate under prolonged cropping, which leads to poor accessibility by roots to otherwise available nutrients;
- danger of soil erosion by water.

For improving the status and availability of nutrients, a basic measure is proper liming. As with other soils, the optimal reaction of these soils also depends on soil texture. However, as the structure of these soils is usually relatively stable owing to iron oxides, a moderately acid pH range between 5 and 6 is frequently optimal. Problems may arise where there are no natural lime supplies within a reasonable distance, as is the case in some large tropical forest regions. Plant-ash from burning trees may serve as a substitute to some extent. However, even if the pH is increased above the toxicity level of Al (pH 4.8), disappointing results may be obtained because of unaccounted-for yield-limiting factors that have to be overcome in order to obtain satisfactory yields.

Acid sulphate soils

The acid sulphate soils, also known as cat clays, have a soil pH as low as pH 3 when drained. This is caused by the presence of dilute sulphuric acid resulting from sulphide oxidation. Some soils are also salt-affected. They often contain toxic amounts of Fe, Al and sulphate but are generally poor in most major nutrients. Such soils often produce very low yields, sometimes less than 1 tonne/ha of grain. However, even small amounts of lime, in combination with PR may increase the yield to 2–3 tonnes/ha. After complete amelioration, which is not easy, these soils can produce yields as high as normal soils.

The best way to manage such soils is amelioration with lime, PR and a general increase in nutrient levels, which requires substantial capital input. However, these soils are generally used in their natural state for growing paddy rice as flooding increases soil reaction. Where the main problem is Fe toxicity, using cultivars with high tolerance to Fe can solve the problem to a certain extent.

Soils of the subtropical arid regions

Arid soils

These soils cover large parts of the arid regions. Soil types at the zonal level often have a light-brownish colour. These soils belong to a variety of soil types depending on the parent material and climatic conditions. However, many of them have similar fertility status. Most of these soils are characterized by a neutral to slightly alkaline soil reaction. They usually have a good soil structure, are not subject to leaching and are rather well supplied with K, S, Ca, Mg, B and Mo. Their major limiting factor is inadequate water. Because of the lack of water, they generally support only sparse vegetation, or none at all. However, more than water is needed in order to make them productive. Their production potential is often considerable except in very sandy and stony soils.

The special problems of nutrient management in arid soils are:

- almost always a severe shortage of water, so that irrigation is usually required;
- sometimes little usable profile depth because of hardened lime crusts in the subsoil;
- low to very low organic matter content;
- low storage capacity for mineral nutrients in sandy soils;
- low content of available and mobilizable nitrogen (owing to low organic matter);
- phosphate deficiency in sandy soils;
- frequent Fe and Zn deficiencies because of fixation under alkaline reaction;
- low biological activity;
- occasional excess of soluble salts, adsorbed Na and B;
- high susceptibility to wind erosion.

As for major nutrients, fertilization with N is almost always necessary. All common N fertilizers act relatively quickly because of the high transformation capacity of these warm soils. On coarse-textured soils, fertilization with P and K is often necessary in order to obtain high yields, but it is less so on medium- and fine-textured soils. Losses of N as gaseous ammonia can occur in the neutral to alkaline range where N fertilizers (particularly urea) are applied to the soil surface and left unincorporated.

Owing to the high soil pH, micronutrient availability poses several problems. In particular, acute Fe deficiency occurs frequently in the form of lime chlorosis. This can be caused by the immobilization of Fe in the soil and also its immobilization in the roots and in leaves. The calcareousness of these soils plays an additional detrimental role. Zn deficiency is frequent, but Cu deficiency is rare. A certain lowering of the high soil pH by acid-producing fertilizers, e.g. ammonium sulphate, is desirable for mobilizing Fe, Mn and Zn.

Vertisols

An important soil type in subtropical zones is the dark clay soils, called Vertisols. With irrigation, their high productivity potential places them among the most productive soils. Vertisols can be shallow to very deep and usually have a neutral to alkaline soil reaction. Their large montmorillonitic clay content (more than 50 percent) makes cultivation of the soil difficult, reduces the permeability to water and reduces aeration.

Vertisols are well supplied with most mineral nutrients and have a high CEC. Their main soil fertility problem is the low level of total and available N. Among nutrients, the application of N, P and Zn is most frequently needed. In the case of N, while leaching losses are small, fertilizers such as urea can be subjected to ammonia volatilization where these are broadcast applied on the dry soil surface. Because of their neutral alkaline reaction, water-soluble sources of P are preferred to untreated PR. Band or spot placement of P is more effective than surface broadcast application. These soils are generally well supplied with K, Ca and Mg.

Fe and Zn deficiency can be a problem in crops grown on such soils, particularly in sorghum, groundnut, sugar cane, upland rice nurseries and fruit trees. The nutrient dynamics in flooded Vertisols change markedly where such soils are submerged for growing rice. Upon submergence, the solubility and availability of P increases, but nitrate in the topsoil can move down into the anaerobic zone and become denitrified if not absorbed by the plant.

Organic soils

These soils contain more than 20 percent organic matter throughout the solum (the upper part of the soil profile consisting of A and B horizons). Such soil can occur independently of climate zones. Organic or bog soils are created where decaying moss and other vegetable matter sinks to the bottom of a lake or pond. True bog soils contain more than 30 percent organic matter by weight. Because of their low specific weight, all data concerning nutrients are referred to in volumes, e.g. nutrient contents per 100 ml of soil.

The WHC of bogs is high. While much of it remains unavailable to the plant, water supply to plants is generally adequate. Poor aeration may limit crop growth where drainage is inadequate. Except for some specific cropping, e.g. by rice, organic soils must be drained for agricultural use. Organic amendments are not required on bog soils, except as nutrient sources. In order to define management strategies for bog soils, they are best divided into raised bog and fen soils.

Raised bog soils

Raised bog soils are highly acidic and poor in minerals. They often require liming before fertilization, but the soil pH should only be raised to a limited extent (unlike mineral soils). Soil supplies of N, P and K are low because of the absence of mineral reserves. Thus, adequate fertilization is necessary. K deficiency is often severe. Relatively small amounts of micronutrients are present, but their availability is generally good (except for Mo). Fertilizer-use efficiency is generally high because immobilization is insignificant as there are no Fe or Al compounds for sorbing phosphate. The deficiency of mineral matter can often be corrected by amelioration with sand. However, this is extremely expensive. Formerly, nutrients were also mobilized by burning bog layers.

Fen soils

Fen soils often occur in large or small depressions in the landscape with mineral soils. They are often rich in lime and mineral nutrient reserves. Therefore, they do not require liming, but acidifying fertilizers should be applied. An abundance of N is characteristic of many fens, providing adequate N for the plants. Their high lime content causes immobilization of phosphate and some micronutrients (especially Mn). An important climate stress is caused by cold conditions in the early stages of plant growth. This increases the importance of proper supplies of nutrients such as K, Mn and Cu in order to improve the tolerance of plants to cold.

Tropical bog soils

Tropical bog soils originating from forest bogs, papyrus marshes, etc. are usually more fertile after drainage than are corresponding bog soils in temperate zones. This is because of the high rate of decomposition of organic matter resulting in an accumulation of minerals in the drained layer. The principal problem in such soils after drainage is their extreme acidity (pH 2–3), often caused by the formation of sulphuric acid as a result of the oxidation of iron sulphide (FeS_2). In this respect, these soils are similar to acid sulphate soils. Such extreme acidity prevents any plant growth either directly or by mobilizing toxic quantities of metal ions. Liming is essential for any practical use, even in less extreme cases. Cropping with drainage causes a substantial loss of organic matter.