Chapter 2
The Soil. Physical, Chemical and Biological Properties

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Abstract This chapter provides a basic description of soil properties and processes, stressing the concept that the soil is a dynamic entity where complex interactions among its biological, chemical and physical components take place. All these components and properties determine the functioning of the soil for different purposes; this functioning is included in the concept of "soil quality". One of the most used definitions of soil quality is the capacity of a soil to function within ecosystem boundaries to sustain biological productivity, maintain environmental quality, and promote plant and animal health (https://www.soils.org/publications/soils-glossary). Land use and management can have a profound impact on many soil properties, thus indirectly affecting soil quality which can result in improvements or constraints for productivity of agricultural lands and for agricultural sustainability in the long term.

2.1 Introduction

From the point of view of agriculture, the soil offers support to plants and acts as a reservoir of water and nutrients. However, in addition to being a physical medium, the soil may be considered a living system, vital for producing the food and fiber that humans need and for maintaining the ecosystems on which all life ultimately depends. Soils directly and indirectly affect agricultural productivity, water quality, and the global climate through its function as a medium for plant growth, and as regulator of water flow and nutrient cycling. The soil structure should be suitable for the germination of the seeds and the growth of the roots, and must have

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characteristics that enhance the storage and supply of water, nutrients, gases and heat to the crop. Soil chemistry is dominated by the interaction between its solid components (primarily the insoluble compounds of silica, calcium and aluminum) and its water phase. Understanding soil chemistry is of paramount importance, since it is the basis of soil fertility and provides the needed knowledge to understand the differences in fertility among different soils and their response to fertilization. Sometimes soil chemistry can have a direct impact on soil physical conditions as in the case of sodic soils with high exchangeable sodium content. The soil also hosts a complex fauna and microbial web involved in many different biological processes, which also affects its physical and chemical properties, and ultimately the productivity of agricultural ecosystems.

For a given soil, its properties depend on the history of the soil formation (Fig. 2.1) and can be substantially modified by human intervention (e.g. through agricultural practices). A proper understanding of soil characteristics and adequate interpretation of the magnitudes of its properties, both combined under the broader term of soil quality (Table 2.1), is required for proper management of agricultural soils.

Fig. 2.1 Soil profiles showing two different degrees of development. Shallow Calcaric Cambisol (*left*) and deeper Vertic soil (*right*)

Table 2.1 Some soil properties normally used in evaluating soil quality

Soil property			
Physical	Soil texture	Bulk density	Infiltration rate
Chemical	Cation exchange capacity	Organic carbon concentration	Soil pH
Biological	Soil respiration	Earthworms presence	Microbial biodiversity

2.2 Dynamics of Soil Formation and Soil Loss

Soil genesis refers to the developmental processes that the soil, as a natural entity, has undertaken over long time periods as the result of the complex interactions of physical, chemical and biological processes, as described in Fig. 2.2. Soil forming processes usually refer to the results of the interaction of these processes of different nature, such as the accumulation of soil components (e.g. organic matter), formation on site of new ones (e.g. clay minerals or oxides), transport within the soil profile (e.g. clay, carbonate or soluble salts), or changes in the aggregation state of soil particles (e.g. formation of a structure). As mentioned in Sect. 2.1., these processes will define the soil type and can strongly affect soil quality.

Available soil depth for plant growth (the depth of the soil profile that can be explored by plant roots also termed rootable soil depth), a determining factor in agronomy since it strongly affects overall crop development and soil productivity, is the result of the balance between soil formation and erosion rates. Soil formation rates are extremely low and mostly related to geology (bedrock properties) and climate conditions. It is usually less than 5 mm per century (although rates range from 0.01 to 40 mm per century). In landscapes that are not under quick geological transformations, eg. alpine uplifting, these soil formation rates tend to be in equilibrium with the erosion rates under natural vegetation. Natural erosion rates range between 0.005 and 60 mm per century, and are mostly the result of water and wind erosion and mass movement by gravitational forces.

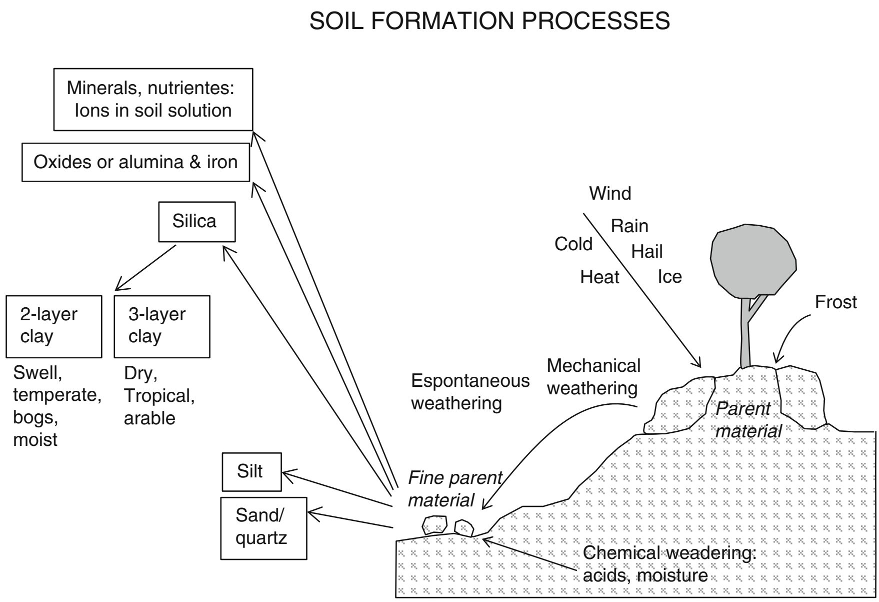

Fig. 2.2 Description of key processes in soil formation

Human interventions mainly by removing the protective plant cover can result in accelerated erosion rates under inappropriate land use or soil management practices. These accelerated erosion rates can reach up to 50 mm per year, resulting in a reduction of the soil profile depth and its degradation. Achieving sustainable erosion rates is a major goal of soil conservation practices. Such rates are defined as those which are either close to the soil formation rates or, at least below a given safe rate (customarily below 10–100 mm per century) that extends far into the future the impact of the imbalance between soil formation and soil erosion rates. The use of soil conservation techniques aim at reducing erosion rates within the range of 0.003–60 mm per century for achieving a more sustainable agriculture.

2.3 Soil Physical Properties: Texture and Structure

Soil physical properties determine many key soil processes (Fig. 2.3), and thus the agronomical potential of a soil. Soil texture, which is a description of the size distribution of the mineral soil particles composing the solid fraction of the soil (from clay <2 μm to coarse particles >2000 μm) is perhaps the most important, since it determines many other physical properties (such as infiltration rate) and some chemical properties (such as cation exchange capacity). Clay mineralogy influences the physical and chemical properties of soils, one of them the swelling-shrinking behavior of the soil, e.g. vertisols, if the clay is an expansive type. Soil structure describes the arrangement of mineral particles and organic matter in the soil, and particularly the arrangement of pores among these particles, and also the stability of this arrangement under external forces such as traffic or rainfall drops. In contrast to texture, soil structure can be substantially modified by soil management. Distribution of pore space and texture determines soil water retention properties (see Chap. 8) which are characterized by the relationship between soil water content

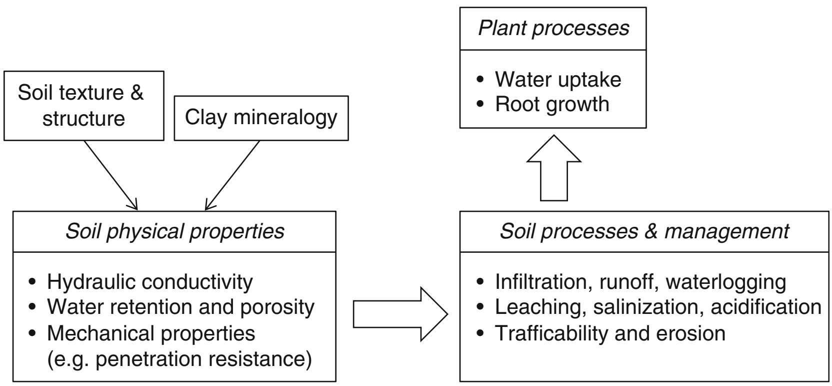

Fig. 2.3 Description of key soil physical properties and related soil processes and management issues (Adapted from Geeves et al. (2000))

and soil water potential (tension). This relation is determined by soil structure and pore size distribution when the soil is at low water tension (wet) and mostly by soil texture at high water tension (dry soil). Bulk density, the ratio between soil dry mass and volume, is a very important soil property influencing soil water retention, aeration, trafficability, and infiltration rate, and is extremely sensible to soil management. Average soil porosity (calculated as P = 1 – bulk density/particle density [taken usually as 2.65 t/m^3]) is a useful parameter. Soil mechanical resistance reflects the resistance encountered in the soil to penetration and is directly related to soil compaction. Mechanical resistance of the soil increases sharply as the soil dries and is used to complement the information provided by bulk density.

Soil permeability is a broad term used to define the ability of the soil for transmitting water. It is important to understand the water dynamics and the water balance of the soil (Chap. 8) and it must be known for accurate management of irrigation (Chaps. 19 and 20). It is determined partly by texture, with sandy soils having high permeability as compared to clay soils and it can be altered by soil management (e.g. tillage, Chap. 17). Other parameters that reflect the water transmission properties of the soil are the infiltration rate, i.e. the rate of water flow through the soil surface, and the hydraulic conductivity, i.e. the ability of a soil to conduct water, a parameter extremely sensitive to soil water content.

Soil particles and the void spaces with their continuity and sizes are all arranged in clusters giving way to a certain structure. Soil physical, chemical and biological properties all influence soil structure by providing means that help held together soil aggregates. Structure affects many soil properties that are relevant in agronomy. The penetration of plant roots, the movement and storage of soil water, the aeration and the mechanical resistance of a soil are some of the more relevant properties influenced by the way soil aggregates are clustered together in a structure. Common management practices such as tillage can change soil structure very rapidly. Such short-term changes are reversible but the long-term degradation of soil structure is a serious problem as it is associated with decreased water infiltration and increased erosion risks. Organic matter plays an important role in facilitating aggregate formation and its long-term decline contributes to the loss of soil structural stability.

2.4 Soil Chemical Properties

2.4.1 pH

Soil pH is that of the soil solution that is in equilibrium with protons (H^+) retained by soil colloids (clays, organic matter, oxides). The soil pH is determined in the laboratory as the pH of soil suspensions in water or salt solutions (usually 0.1 M $CaCl_2$ or 1 MKCl). The degree of acidity or alkalinity of a soil is a very relevant property affecting many other physicochemical and biological properties. Problems derived from *acidic soils* or acidification of agricultural soils can be overcome by increasing base saturation and pH with soil amendments (liming). Basic or alkaline soils are the consequence of the buffering of soil pH by base elements or by the presence of buffering compounds such as carbonates. *Calcareous soils* are those with an appreciable concentration of $CaCO_3$ which buffers soil pH near 8.5; the presence of other carbonates (Mg or Na in sodic soils) can buffer soil pH well above 8.5. The pH of a calcareous soil cannot be changed due to its high buffering capacity and its limitations for agricultural use, mainly related to restrictions in nutrient uptake and in plant nutrition, may be overcome with special fertilizer products and fertilization strategies.

Some of the soil fertility features affected by soil pH include:

(a) Availability of mineral elements to plants in the soil. At low pH, the risks of deficiency of base nutrients (Ca, Mg, and K) increases due to their low content; also the solubility of Mo and P compounds is decreased, thus decreasing its availability. On the contrary, Al concentration is increased (usually at pH <5.5) and thus its toxicity effects; the concentration of Fe and Mn, essential nutrients for plants, can be high enough at low pH as to cause toxicity. At high pH, the solubility of many metals and trace elements is decreased, including essential nutrients for plants such as Fe, Mn, Cu or Zn. Deficiency of Fe, known as *iron chlorosis*, is frequent in basic soils (typically in calcareous ones).

(b) Biological properties: extreme pH values decrease microbial activity in soils, which affects many soil processes (for instance, soil organic matter decomposition, nitrification, and biological N_2 fixation under acidic conditions, see Chap. 24).

(c) Physical properties: low Ca concentration in acidic soils is usually related to an increased dispersion of colloids if Al is not present at high concentration. Thus, acidic soils can have poor soil physical properties, including poor structural stability or low permeability.

2.4.2 Redox Status

The redox status of a soil is determined by the availability of electrons which can participate in redox reactions (pE, – logarithm of the activity of electrons) and it is controlled by physical conditions (water content and porosity) and biological activity. It affects the solubility and speciation of elements with different redox states, such as N, S, Fe, Mn, some toxic trace elements (e.g. As, Se), and even C. Reducing conditions in agricultural soils usually occur at very high water contents (saturation) since, under these conditions, oxygen is quickly consumed by biological activity. Reducing conditions increase the solubility of Fe and Mn compounds, enhancing the uptake of these nutrients by plants (which can become toxic) and of elements adsorbed on Fe and Mn oxides (e.g. P and heavy metals).

2.4.3 Ion Retention in Soils

Ions can be retained in soils by precipitation and adsorption processes. *Precipitation* means the formation of a new solid phase, e.g. when P fertilizer is applied to a soil with a high Ca concentration, new crystals of Ca phosphates can be formed. *Adsorption* is the accumulation of chemical species (sorbate) on the surfaces of an existing solid in the soil (sorbent). Precipitated and adsorbed species are in equilibrium with the soil solution (precipitation/dissolution and adsorption/desorption equilibria).

Adsorption can be the consequence of chemical reactions with functional groups of sorbent surface which is sorbate specific (e.g. P on hydroxilated surfaces), or electrostatic attraction by sorbent surface which is not sorbate specific. Charge associated with mineral and organic surfaces can be permanent and variable. Permanent charge arises from isomorphic substitution within clay minerals. Variable charge is the result of unsatisfied bonds at the edge of minerals and organic matter and is pH dependent.

2.4.3.1 Exchange Capacity

Exchangeable ions are those weakly adsorbed by soil particles that can be displaced from sorption sites by other ions in the solution. Exchangeable ions are essential for maintaining plant nutrient reserves in the soil.

Cation exchange capacity (CEC) is measured as the amount of cations (equivalents or moles of charge) which can be extracted by a high concentrated cation solution (usually, 1 M K^+ or NH_4^+). The CEC is usually dominated by Ca, Mg, Na, K, Al, and protons. The selectivity or relative affinity of cation by sorbent surfaces is based on the ion's charge and size: the smaller the hydrated radius (cation + water molecules strongly interacting by ion-dipole interaction) the greater the affinity (ions with small dehydrated radius have large hydrated radius), and the higher the valence the greater the exchanger preference for the cation; the affinity scale for dominant cations in soils can be summarized:

$$Al^{3+} > Ca^{2+} > Mg^{2+} > NH_4^+ > K^+ > Na^+$$

Base saturation is defined as ratio of base exchangeable cations (Ca, Mg, K, and Na) to total CEC, which decreases at decreased pH in the soil. Ca, Mg, and K are nutrients for plants; thus a high base saturation means a greater nutrient reserve than a low base saturation for the same CEC. Low base saturation related to soil acidity can determine Ca deficiency for crops. In order to guarantee good physical soil properties (soil aggregation, structure stability, good aeration, and drainage) and nutrition for crops, Ca must be the dominant cation in the exchange complex (ideally $>50\,\%$ of CEC); also it is desirable that the Ca/Mg ratio would be 5–10 and the K/Mg ratio 0.2–0.3 in order to avoid nutritional disorders (antagonisms) for plants which can lead to a deficiency of a nutrient promoted by a high level of the antagonistic nutrient.

2.4.4 Salinity and Sodicity

Salinity is defined as a high concentration of soluble salts (more soluble than gypsum) in soils. A saline soil has a soluble salt concentration high enough to negatively affect the growth and development of most cultivated plants. Classification of saline soils and the assessment of the negative effects of salinity on crops are based on the electrical conductivity (EC) of the saturation extract of the soil. If the EC of the soil is higher than 4 dS/m it is defined as saline. There is ample variation in the responses to salinity among different crops (Chap. 22). Crops highly sensitive to salinity (e.g. carrot, bean, strawberry) are affected by EC values slightly above 1 dS/m. On the opposite side tolerant crops such as barley and sugar beet among others, can tolerate EC levels above 4 dS/m. Impact of salinity on plant growth is caused by osmotic effects (decreased water potential in soil), and from specific toxicity, typically due to high Cl or Na concentrations.

Sodicity is referred to a high exchangeable Na concentration in soils. Since Na salts are common in saline soils, both problems are usually related. Na is a monovalent cation with a big hydrated radius. Hence, high contents of Na adsorbed on soil colloids promote their dispersion, thus negatively affecting soil physical properties. A soil is classified as sodic if exchangeable Na accounts for more of 15 % of the CEC (Exchange Na percentage –ESP– >15). However, crops sensitive to Na toxicity are affected at ESP >7 (e.g. peach, citrus, strawberry). Problems in crops tolerant to Na toxicity (e.g. cotton or rye) usually are derived from physical degradation of soil. Soils with EC $>$ 4 dS/m and ESP >15 are classified as saline-sodic. Problems derived from sodic soils can also be related to their very high pH values (usually >8.5 if the soil is not saline).

Chapter 22 expands on the salinity problem in agriculture and describes the approaches for its management and control.

2.5 Soil Biological Properties

Soils host a complex **web of organisms** (Fig. 2.4) which can influence soil evolution and specific soil physical and chemical properties. For instance earthworms activity increases infiltration rate, or microbial activity decreases soil organic matter due to mineralization.

Soil biological properties are also interconnected with other soil physical and chemical properties; e.g. aeration, soil organic matter or pH affect the activity of many microorganisms in soils which in turn perform relevant activities in carbon and nutrients cycling. Examples of this interconnection were given in Sect. 2.4.

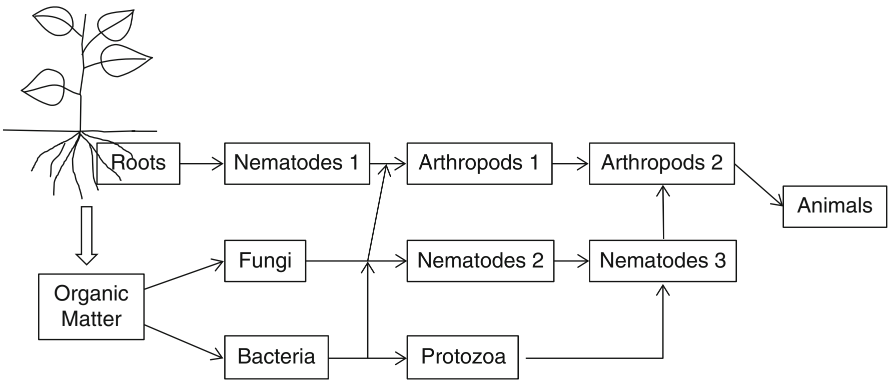

Fig. 2.4 Soil food web

Thus, changes in soil properties due to management can significantly affect biological properties in soils, some of them being extremely sensitive to soil management; e.g. soil microbial activity can be greatly increased by improved drainage, liming or organic amendments. That is why some soil biological properties can be used as indirect indicators of appropriate soil management and good soil quality, like soil respiration rate or some enzymatic activities that can be derived from living organisms in soil.

Soil organic matter is a key factor affecting biological activity in soils. It is the carbon source for many organisms, including soil microbiota. Not only the amount, but also the type of organic compounds in the soil determines its biological activity; e.g., microbial activity is greatly increased by incorporating fresh organic residues (such as green manure or crop residues), which can be readily mineralized by microbes. On the other hand, stable forms of organic matter (humic and fulvic compounds), which constitutes most of the organic matter of soils in temperate regions, is not a very suitable carbon source for soil microbiota, which explains the long half-life of these compounds in soils (usually >1000 years); thus, stable organic compounds do not contribute significantly to soil microbial activity but constitutes an stabilized stored soil C pool which is very relevant to the C global cycle, partially buffering the consequences of increasing C emissions to the atmosphere.

The **rhizosphere** is the volume of soil altered by the root system and is the part of the soil profile where the concentration of suitable C sources for many microorganisms is greatest. Organic compounds exuded by plant roots (including organic anions of low molecular weight) alter soil chemical properties and greatly increase the biological activity in comparison to the bulk soil. The rhizosphere is a space of intense interaction of plant roots with soil microorganisms. Rhizospheric microorganisms can significantly affect plant development through the production of growth regulators, by decreasing the incidence of plant diseases, and by increasing nutrient availability to plants.

Table 2.2 Some soil biological properties

Property	Comments
Respiration rate	CO_2 evolution under standard laboratory conditions or at the field
Potential N or C mineralization	Increase in mineral N or C content under standard laboratory conditions
Earthworms	Density of earthworms
Bacterial biomass	Total bacterial biomass for a given soil mass
Bacterial diversity	It can be determined by functional groups, or describing genetic diversity
Presence of pathogens	By different pathology techniques, from cultures to DNA profiling

Understanding soil biological properties is important for soil management but also for prevention and control of crop pests and diseases. Many of the properties indicated in Table 2.2 are a description of the diversity and activity of parts of the soil food web, or of related properties such as soil respiration rate or organic matter content.

2.6 Nutrient Cycles and Balances in the Soil

Nutrient in soils are present in different chemical forms, which can remain in solution or bound to soil particles. Exchange of nutrients between different forms or "soil pools" is governed by physical, chemical, or biological processes. All these processes are included in the concept of "nutrient cycle" in soils. Since the soil is not a "closed system", gains or losses of nutrients from the soils occur to/from the atmosphere or water courses (leaching or erosion), which links the "soil nutrient cycle" with the "global nutrient cycle" in the Earth crust. The soil and global nutrient cycles are affected by human activities. In agricultural soils, fertilization clearly alters the cycle, introducing nutrients in the system. Without this supply, the natural input of nutrients in soils would be much lower than typical crop extractions, thus inducing a "negative balance" which would cause a progressive depletion of nutrients and thus a progressive loss of soil fertility.

A general nutrient cycle is represented in Fig. 2.5. The flux of nutrients to plant roots comes from the soil solution, mainly as dissolved ions. The "labile nutrient pool" is that readily equilibrated with the solution, as adsorbed ions described in Sect. 2.4.3.1, those precipitated as soluble salts, or those present in organic compounds which are readily mineralized. The "available pool" of nutrients is the amount in solution plus that readily equilibrated with the solution ("labile forms"); for a given nutrient it can be considered the amount that can be extracted by successive crops until severe deficiency of this nutrient appears in crop.

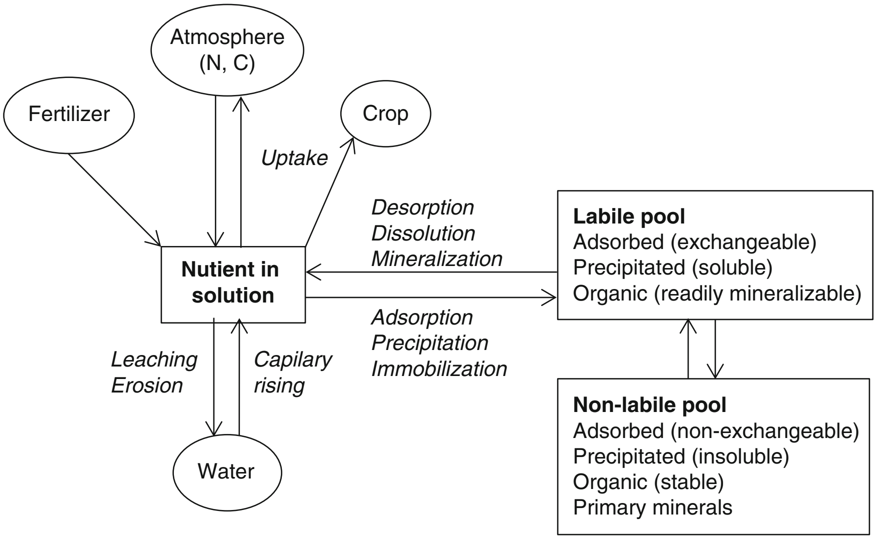

Fig. 2.5 General cycle of nutrients in soil. In italics physical, chemical or biological processes involved in nutrient cycle. Residue incorporation to soil involves nutrient recycling: not only in soluble forms (e.g. K); most in organic forms or organic bound forms that can become part of the labile or non-labile pool. Exchange between labile and non-labile forms implies the same processes that those involved in the equilibria between labile forms and solution

Chemical (e.g. adsorption/desorption or precipitation/solubilization) and biological (immobilization/mineralization) interactions affecting nutrient equilibria and exchange rates between the labile fraction of the soil solid and solution phases, ultimately determine the solution ionic activities and the transport of nutrients to plant roots.

Accurate estimation of fertilizer requirements in modern agriculture is based on the knowledge of nutrient cycles and the precise estimation of available nutrients pools in soils through chemical methods. *Mobile nutrients* are considered those which are not bound to soil particles. Nitrogen, in spite of ammonium being adsorbed, it is readily transformed to nitrate, which is not adsorbed to soil particles. In agricultural systems, where the contribution to available nutrient pool by organic matter mineralization can be low, the major contributors to the available pool of mobile nutrients are usually inorganic ions in the soil solution. *Immobile nutrients* are those which are bound to soil particles through adsorption or precipitation processes, being in this case the labile pool the major contributor to the available pool. Immobile nutrients, such as P, K, Ca, or Mg, are less susceptible of loss through leaching; on the other hand, the nature of chemical reactions involved in their retention cause that only part of the nutrients supplied as fertilizer are available to plants.

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