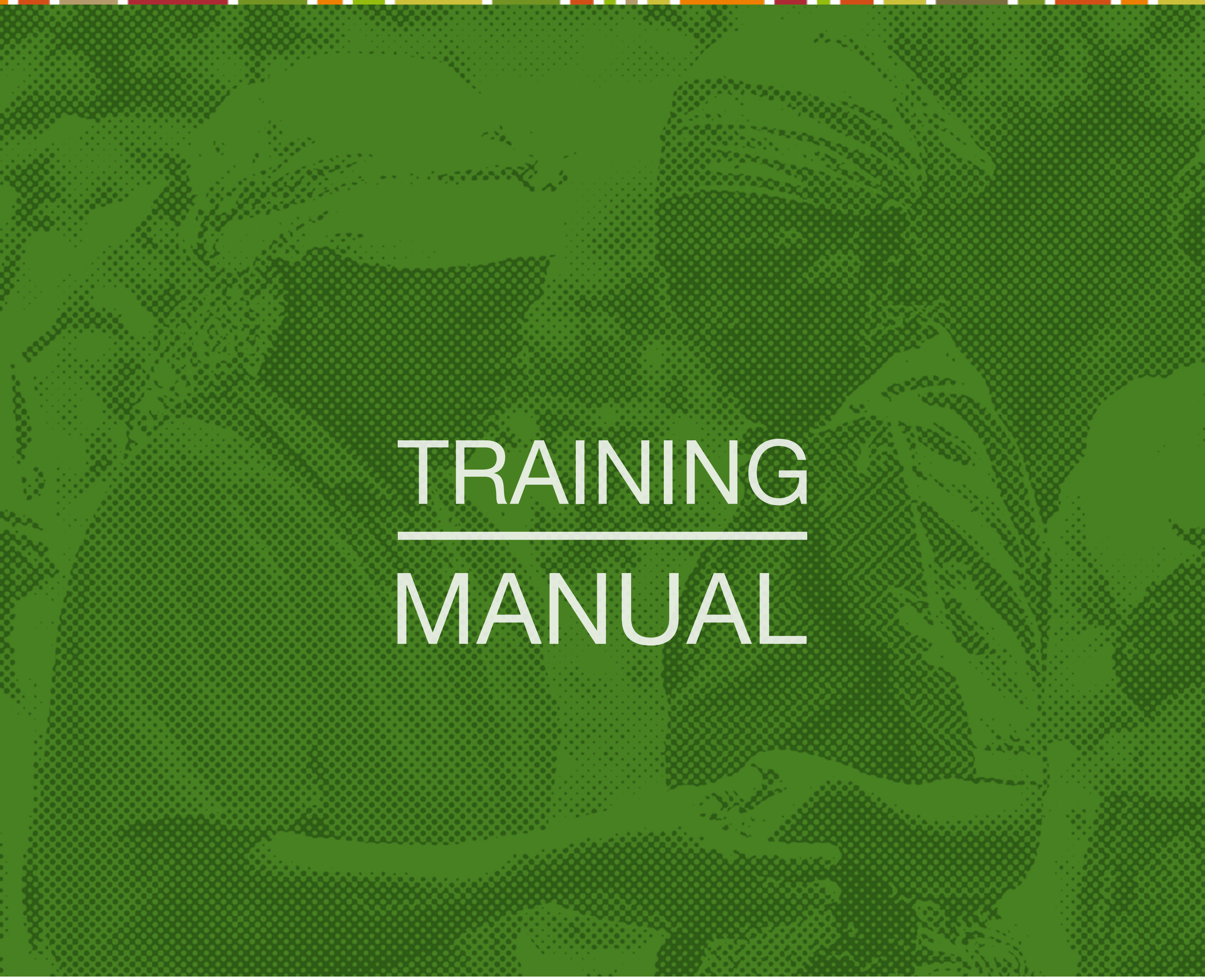

TRAINING MANUAL

- ENVIRONMENTAL MANAGEMENT -

SUSTAINABLE SOIL MANAGEMENT

COLEACP

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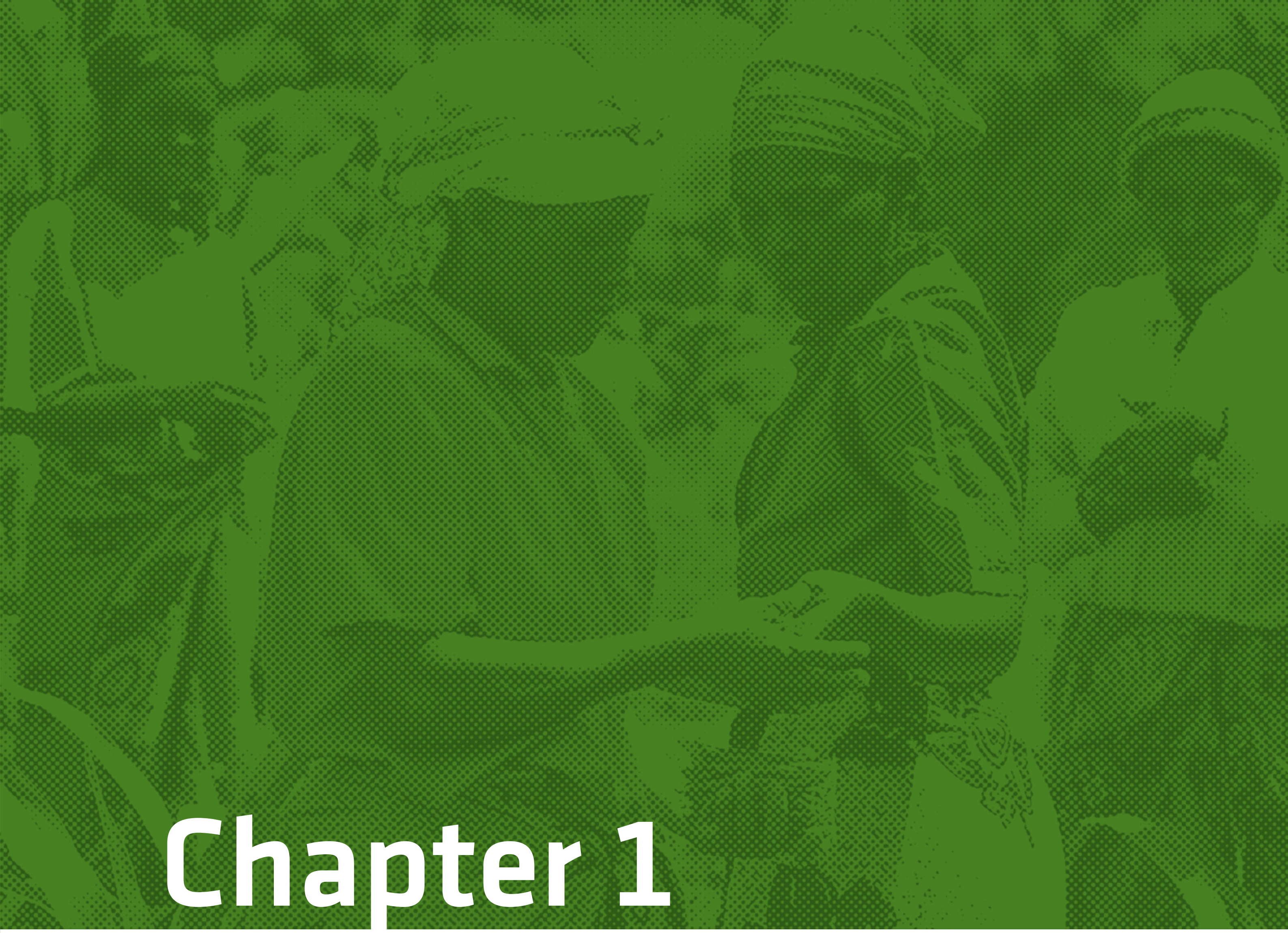

Chapter 1

Foundations of soil science

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LEARNING OUTCOMES

After reading this chapter, you will:

- understand what a soil is, including its composition, primary fractions and major constituent elements, and know why it should be managed sustainably
- understand how a soil is formed from the parent rock, and the factors that help to determine the soil's characteristics
- understand what a soil profile is, and identify types of soil that are representative of various African, Caribbean and Pacific (ACP) regions and climates
- be able to identify the main properties of soils (physical, chemical and biological)
- know the different functions of a soil.

1.1. INTRODUCTION TO SOIL SCIENCE

1.1.1. Why is soil important?

Human life is dependent on agriculture. The capacity of the land to support agricultural activities provides a primary measure of its economic value, and is generally measured on the basis of the soil's capacity to assume certain key functions that sustain crops. It is not by chance that the richest societies have developed in areas where the soil's inherent fertility is high.

The word 'soil' indicates the unconsolidated mineral and organic materials on the surface of the land that serve as a natural medium for plant growth. Soil is a fundamental attribute that determines primary productivity and supports life on Earth. Soil is inseparable from land, the primary input factor for agricultural production (Fairhurst, 2015).

Soil is the farmer's main **asset** and, if managed well, it will add long-term economic value to the land. That is why it is important to talk about 'sustainable soil management'. The aim of integrated soil fertility management is to promote the optimal and sustainable use of nutrient reserves in soil, including application of mineral fertilisers and organic soil improvers (amendments).

Managing soil fertility and developing sustainable production systems is an essential concern in conventional agriculture, and even more so in organic farming. Sustainable soil management is a requirement of certain **standards**. For example, the Global Good Agricultural Practices (GLOBALG.A.P.) standard has specific requirements regarding soils, maintaining soil structure and preventing erosion. Similarly, Fair Trade specifications focus on methods for organic agriculture with a view to protecting and maintaining biodiversity. Fair Trade promotes the limited and safe use of chemicals as well as effective waste management, erosion control, soil fertility maintenance and responsible water management. The felling of primary forests is prohibited (Info Label, Fair Trade: Max Havelaar).[1]

1 https://www.labelinfo.be/fr/label/fairtrade.

Regarding **organic farming**, among its general objectives, European Commission (EC) Regulation No. 834/2007[2] seeks to establish "a sustainable management system for agriculture that respects nature's systems and cycles and sustains and enhances the health of soil". The Regulation therefore requires effective soil management that enables soil fertility to be maintained or enhanced (e.g. under Art. 12, the fertility and biological activity of the soil are maintained and increased by multi-annual crop rotation), and also requires the prevention of soil erosion and compaction.

Farmers can exploit the potential of their soil to ensure high quantity and quality of production, but they must be careful not to deplete their soil capital through overuse of a resource that many (wrongly) believe to be unlimited. Lack of soil fertility causes reduced yields and encourages the development of numerous plant diseases. If soil fertility is poor, crops lack strength and become more susceptible to diseases and parasites. These lead to a further reduction in productivity which threatens the livelihoods of rural communities.

To maintain **soil fertility** in the long term, we must first understand what constitutes a soil, how it works, the relationships between its various component elements, the impacts of various agricultural practices on fertility, and the means of preserving fertility and restoring it where necessary. Understanding soil requires a knowledge of organic matter and nutrients, as well as important concepts in soil science such as texture, structure and humification; the role of soil organisms, soil aggregates and colloids; and a study of the chemical properties of soil such as pH, which indicates soil acidity, and cation exchange capacity (CEC), which determines the capacity of the soil to hold certain elements.

Despite the complexity of soil management, to secure their yields, farmers must be able to estimate the quality of their soil. This includes being able to determine important factors such as the texture and structure of the soil, and to judge its fertility via organic matter levels, balance of nutrient reserves, measurement of soil acidity or porosity, etc.

The fertility of soil depends on its origin (alluvial soils, soils that develop on different types of parent rock) as well as its texture, structure, organic matter content, and fertility management by farmers in the past. A good indicator of the fertility of the soil is its colour. Dark coloured soils are generally rich in organic matter (carbon-rich). Red soils, typical in much of sub-Saharan Africa, are generally acidic and lacking in organic matter. As the physical base for crops, a fertile soil must have a structure and depth that enables plants to expand their roots and anchor themselves, and that retains moisture and drains excess water. Its composition and pH must provide a good supply of nutrients, including nitrogen, phosphorus, potassium, and other trace elements. A fertile soil is a living soil, rich in earthworms, insects, nematodes, fungi and bacteria, which contribute to the recycling of organic matter and maintain good porosity. Finally, a fertile soil can accommodate beneficial organisms.

Through their farming practices, farmers can either enhance or reduce the fertility of their soil. They can improve or destroy the soil's structure, and enrich or deplete its nutrient stock. The incorporation of mineral and organic fertilisers, crop residues,

2 Regulation on organic production and labelling of organic products, *OJEU*, L 189/1).

manures, composts and green manures will enrich the soil with various nutrients, while harvesting removes some of them. There are therefore **nutrient cycles** in the soil that can be in or out of balance. Without human intervention, nutrient cycles in the soil are generally in balance, but in practice this situation is rare.

According to Wopereis *et al.* (2009: pp. 57–58), in sub-Saharan Africa many smallholders are forced to draw more nutrients from the soil than they return, making their land increasingly fragile. On the uplands, slash-and-burn practices reduce the carbon content of the soil, and the first rains can leach significant quantities of other nutrients. Farmers may have no choice but to use the same plot over several years without adding inputs. With each harvest, nutrients are therefore drained from the land without being replaced. One practice for improving soil fertility is to leave a plot fallow for a certain time. Unfortunately, the shrinking size of land holdings in Africa generally prohibits this practice.

Excessive export of nutrients that are not compensated for results in a long-term **imbalance of nutrients** in the soil. Soils on lowlands are generally more robust and fertile than soils on uplands, but poor management of soil fertility can cause long-term nutrient deficiencies. It has been estimated that over the past 30 years, on average 22 kg of nitrogen, 15 kg of potassium and 2.5 kg of phosphorus have been lost per hectare per year on 200 million hectares of cultivated land in sub-Saharan Africa (excluding South Africa) (Wopereis *et al.*, 2009). The effect of this negative balance is to deplete the soils and reduce agricultural production.

While there have been concerns about soil quality throughout history, international awareness about the importance of sustainable conservation and management of soil resources, and concrete measures to protect them, are very recent (similarly to protection of the two other primary resources: water and air).

According to Winfried Blum International Union of Soil Sciences, proposals for a convention on the sustainable use of soils were adopted soon after the Earth Summit (held in Rio de Janeiro in June 1992) and came into force in December 1996. However, the efficacy of the protection measures to be adopted depends largely on having reliable diagnostic methods to assess soil functions and changes in soil quality. There are numerous definitions of soil quality in response to social and scientific concerns. Still, global issues of food security call for a response to the challenge of environmentally sustainable agriculture focused on soil and environmental protection.

1.1.2. What is sustainable soil management?

This chapter discusses 11 main characteristics that form the basis of sustainable soil management (see next box).

Characteristics of sustainable soil management

- Minimal rates of soil erosion by water and wind.
- Soil structure is not degraded (e.g. by soil compaction) and provides a stable physical context for movement of air, water and heat, as well as root growth.
- There is sufficient surface cover (e.g. from growing plants, plant residues) to protect the soil.
- The store of soil organic matter is stable or increasing, and ideally close to the optimal level for the local environment.
- Availability and flows of nutrients are appropriate to maintain or improve soil fertility and productivity, and to reduce their losses to the environment.
- Soil salinisation, sodification and alkalinisation are minimal.
- Water (e.g. from precipitation and supplementary water sources such as irrigation) is efficiently infiltrated and stored to meet the requirements of plants and ensure the drainage of any excess.
- Contaminants are below toxic levels – those that would cause harm to plants, animals, humans and the environment.
- Soil biodiversity provides a full range of biological functions.
- Soil management systems for producing food, feed, fuel, timber and fibre rely on optimised and safe use of inputs.
- Soil sealing is minimised through responsible land-use planning.

(Source: FAO, 2017)

1.1.3. What is a soil?

1.1.3.1. Definition and importance of soil

Like many common words, the word 'soil' has several meanings. In its traditional meaning, soil is a natural medium for plant growth. **Soil has also been defined as a natural body comprising superimposed layers** (or horizons, designated by the letters O, A, B, E, C, etc.) that consist of weathered mineral and organic material, air and water. Soil from the Earth's crust is differentiated by the significant presence of life. As Leonardo da Vinci put it: "We might say that the earth has a spirit of growth; that its flesh is the soil" (Richter, 1970).

Soil is the interface between land, air and water. It is the end product of the combined effect over time of climate, topography and the activity of organisms (flora and fauna, and humans who cultivate the soil) on base materials (rocks and minerals). Section 1.2 describes in detail the processes that lead to soil formation.

Soil is an extremely complex, variable living environment. It is home to the majority of the biosphere. **Soil is one of our most precious natural resources.**

Soil is a source of food, biomass and raw materials. It performs the functions of storage, filtration and conversion of numerous substances, including water, nutrients and carbon. It is the world's largest carbon sink (1,500 gigatonnes). These functions must be protected due to their socio-economic and environmental importance. The various functions of soil are described in section 1.5.

In humid tropical areas, a soil can be built up from a sandy base over 200 years. However, this process normally takes more time. Under most conditions, soil is built up at a rate of just 1 cm every 100 to 400 years, and it takes 3,000 to 12,000 years to form a layer that is sufficient to create a productive soil. Since soil formation is an extremely slow process, it can be concluded that soil is essentially a non-renewable resource.

Soil degradation therefore poses a serious problem. It is caused or aggravated by human activities such as unsuitable agricultural and silvicultural practices, industrial activity, tourism, urban and industrial expansion, and large-scale construction. The sources and consequences of soil degradation (erosion, salinisation, pollution, compaction, etc.) will be explained further.

According to the Soil Atlas of Africa (Jones *et al.*, 2013), some African soils are very old and reflect radical changes in climate and vegetation. Red soils dominate, indicating a high level of iron oxides. Almost half of Africa's total land area is characterised by sandy (22%), rocky shallow (17%) and poorly developed (11%) soils.

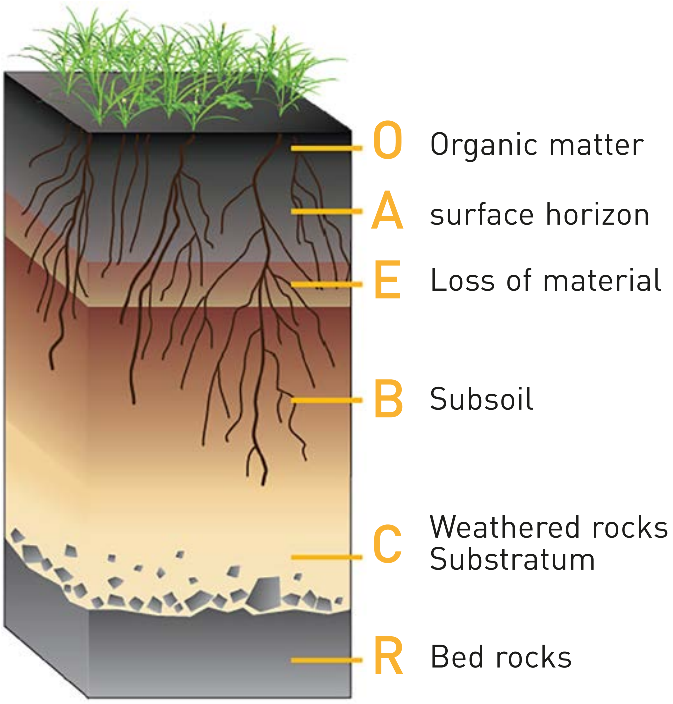
1.1.3.2. Soil composition

Soil generally consists (by mass) of minerals (up to 95%), water (15–35%), air (15–35%) and organic matter (0–5%). In arid regions, the quantity of water and organic matter is significantly lower. Table 1 shows the three phases of soil:

- **solid** phase, composed of mineral constituents (sand, clay, etc.) and organic constituents (organic matter)
- **liquid** phase (soil solution), consisting of water in which soluble substances such as salts are dissolved; these are derived from the weathering of rocks, mineralisation of organic matter and inputs from humans (e.g. soluble fertilisers or fertilisers capable of being solubilised)
- **gaseous** phase (soil air or vapour phase), composed of the same gases as air, plus gases from the decomposition of organic matter.

Table 1: Constituents of soil

Solid		Liquid	Gaseous
Mineral	Organic	Soil solution	Soil air
Fine earth of the soil: • clays • fine silts • coarse silts • fine sands • coarse sands	*Fresh organic matter*: • constituents of plant tissues (cellulose, hemicellulose, tannins, etc.) • animal droppings and dead animals	*Soil water and dissolved soluble elements*: • organic substances (organic acids, etc.) • ions in the soil water: Ca^{2+}, Mg^{2+}, K^+, Na^+, NO_3^-, PO_4^{3-}, etc.	*Constituents of the air*: • N_2, O_2, CO_2 • Gas from the activity of soil animals and decomposition processes: • CO_2, H_2, CH_4, etc.
Coarse elements: • gravel • stone • rock • boulders	*Humic materials*: • converted organic matter		



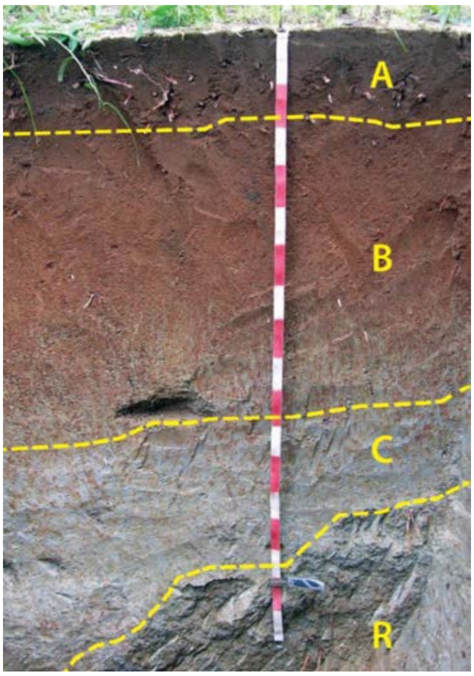


Figure 1 - Theoretical soil profile (left) and photo of a soil profile (right)
Source: Jones *et al.* (2013)

To understand how these various constituents are organised, a vertical cut of the soil, called a **profile**, can be made to observe the different layers that are more or less parallel with the surface. They are distinguished by their composition, colour, structure and texture (e.g. dark layers generally contain more organic matter). These layers, called **horizons**, are the result of several geological, physical, chemical and biological processes that have influenced the parent materials (Figure 1). Most soils usually have three or four horizons, designated by the letters O, A, E, B, C, etc. We will discuss how soils form from the parent rock.

Table 2: The main soil horizons Source: Jones *et al.* (2013)

O horizon	The O (organic) horizon is the superficial layer where organic matter that will decompose and gradually evolve accumulates. This is the **surface layer** (also called the **litter layer**), comprising plant debris and humus. It contains a large number of organisms (e.g. burrowing species) that will fragment the litter into small pieces and integrate it into the soil. Through decomposers, soil temperature and humidity, the debris is decomposed and changed into humus. The humus is filled with nutrients, and water infiltration allows those nutrients to descend to the A horizon.
A horizon (mixed horizon)	The A horizon consists of mineral elements and humus. It is composed of a mixture of humus and rock particles, also known as **topsoil**. It is dark coloured or black (the darker the colour, the higher the organic matter content). It is the horizon most affected by erosion and biological transformation. This layer is essential to plant development because it is filled with organic matter and minerals. Most biological activity in the soil occurs here (including microorganisms, bacteria and soil fungi). Certain insects, rodents and worms that burrow into the soil ensure this layer is aerated. This is where decomposition of litter and roots, release of nutrients, and formation of organic acids occur.
E horizon	The E (eluvial) horizon may appear in mineral soils when materials such as organic matter, clay, iron and aluminium have been leached by percolation to deeper layers. E horizons are generally lighter in colour (but not always) and have a coarser texture.
B horizon (accumulation horizon)	The B horizon is the mineral **subsoil** containing one or more layers with more vivid colours (e.g. red) than the O and A horizons. It is an intermediate horizon that appears in leached soils. It is rich in fine elements (clays, iron and aluminium hydroxides, humic compounds), stopping their descent at this level when they encounter a mechanical obstacle associated with **porosity** (just as flour poured through a jar containing marbles above sand would flow down through the marbles but not the sand). B horizons contain much less organic matter (hence the difference in colour); plant roots and soil animals use the water and nutrients stored here. This is the site of physicochemical and **biochemical** processes leading to the destruction of **minerals** in the soil (**mineral weathering**). Its brownish, yellowish or reddish colour comes from the iron oxides derived from mineral weathering, while the greyish tones result from a chemical reaction in the reducing environment.
C horizon	The C horizon comprises loose material from the subsoil. It contains pieces of fragmented, partially deformed rocks and there is a lack of organic matter.
R horizon	The R (bedrock) horizon is the layer of **parent rock** from which the soil has been formed by the elements and events over time. It can be sandy, clayey or hard.

Note that there are other horizons. For example, the B horizon is constituted from bedrock elements that are completely altered, reduced to very small particles, and also incorporates clay and other materials from other sources. The S horizon is constituted only from bedrock elements, with no clay or other materials.

1.1.3.3. Main mineral constituents of soil

Coarse elements (2 mm to 20 cm)

The coarse elements form the **soil skeleton**. Where they constitute the main part of the soil's composition, they create skeletal soils (e.g. certain mountain soils). The coarse elements:

- constitute the soil's mineral reserve – their chemical weathering releases mineral elements that contribute to plant nutrition (note, however, that quartz grains are almost chemically unalterable and cannot contribute to plant nutrition)
- increase the soil's permeability to air and water
- reduce the volume of soil that can be used by plants (by reducing the proportion of fine soil available to roots)
- may affect the heat of soil, acting as a heat reservoir (e.g. calcareous soils)
- may help to build up a water reserve – some porous rocks (e.g. limestone) can retain a little water.

Coarse sands (200 µm to 2 mm)

In the soil, coarse sands:

- promote the penetration of water and air, making the soil permeable
- retain little water, so the soil acts as a filter
- facilitate temperature exchanges, so the soil heats up quickly in spring
- cannot agglomerate into clods, so the soil is light (and can therefore be quite susceptible to erosion), and easily penetrated by plant roots.

Fine silts and fine sands

These create **running sandy soil**: the soil tends to settle on the surface due to rain and to form crusts (deterioration of surface soil structure). They tend to retain water by blocking its deep infiltration: the soil is impermeable on the surface and asphyxiating for the roots (see Figure 2).

Clays

Clay minerals can be present in various states – dispersed, aggregated and flocculated – linked to the nature and concentration of cations (ionic strength), particularly of sodium (Na^+) and calcium (Ca^{2+}). By partnering with organic matter, fine clay particles contribute to the formation of mixed colloids (the clay–humus complex) responsible for specific or non-specific absorption reactions (or surface fixation), allowing the fixation of cations or anions (including charged molecules such as pesticide residues and other soil contaminants).

Figure 2 - Running sandy and compacted soil after rain
Source: www.agriculture-de-conservation.com

1.1.3.4. Main organic constituents of soil

Origin of humus

Organic debris may be of plant or animal origin, and may be left on the soil (e.g. natural leaf fall, crop residues or senescence) or buried in the soil (by humans and/or animals). The transformation of this debris through decomposition, caused by various agents, leads to the formation of humic materials. The organic matter is referred to as 'fresh' before it is converted into humus (Gobat *et al.*, 2003). Plant substances account for the vast majority (99%) of the material involved in the roduction of humus.

The **fresh organic matter** that generates humus consists of:

- sugars, starches and other water-soluble carbohydrates
- hemicellulose
- cellulose, polysaccharide from condensation of glucose molecules
- lignins, which are the result of polyphenol condensation
- tannins
- fats, waxes, oils, etc.
- proteins and derivatives
- mineral constituents (ash): phosphorus, sulfur, potassium, calcium, etc.

The fresh organic matter in the soil plus evolved products – the **humic substances** – constitutes humus in the strict sense of the word. Humic substances are organic macromolecules which are colloids. These are extremely fine particles that do not form a true solution in the soil's aqueous solution, but form a suspension (**colloidal suspension**). These colloids are highly reactive; they consist mainly of carbon, oxygen, hydrogen, nitrogen, and occasionally sulfur and phosphorus. Humic substances are classified on the basis of their molecular size, and also on their solubility in an aqueous medium.

A distinction is made between humic acids and fulvic acids.

- **Humic acids** constitute a significant quantity of the organic carbon dissolved **in the soil solution**, and are one of the most significant fractions of humus. They are not very mobile, but are capable of binding more or less strongly, depending on their type, with other bodies present in the soil, and particularly with clay. The complex formed with clay (clay–humus complex) is very stable, and in this case the humic acids are grey (Figure 3).

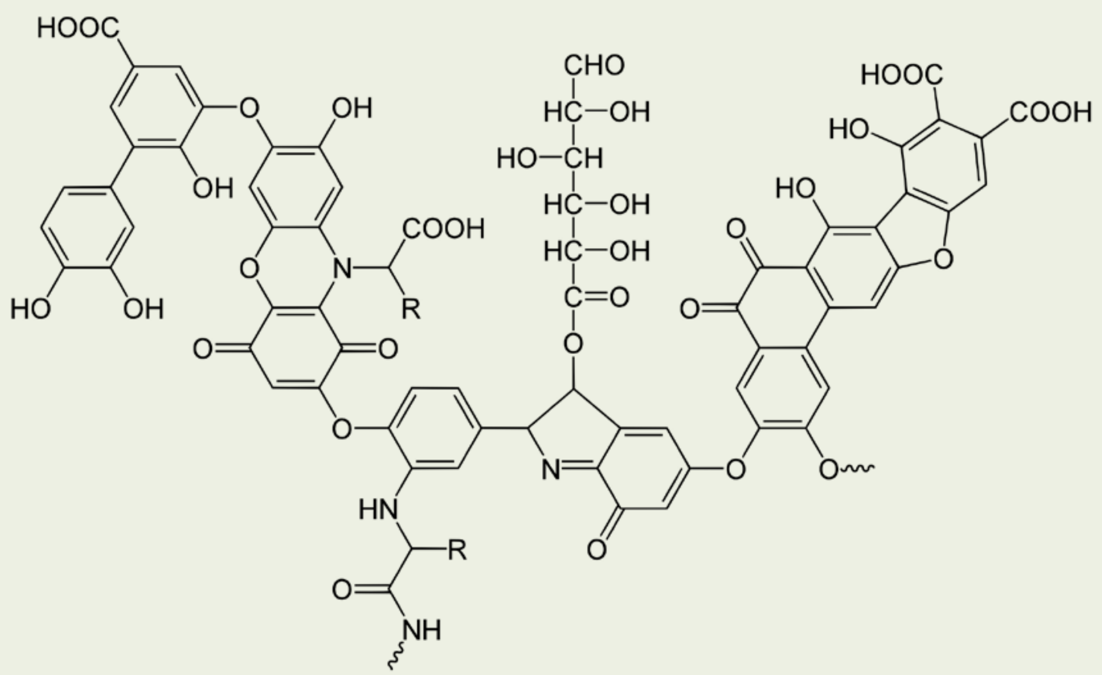


Figure 3 - A humic acid

- **Fulvic acids**, which are more mobile, constitute the primary part of the organic carbon dissolved **in natural waters**. They are quickly carried away by infiltration waters, which they load with the clay and iron to which they are bound. Through this mechanism they are the main agents of iron leaching. They have the capacity to chelate several soil minerals and to promote their uptake by plants (Figure 4).

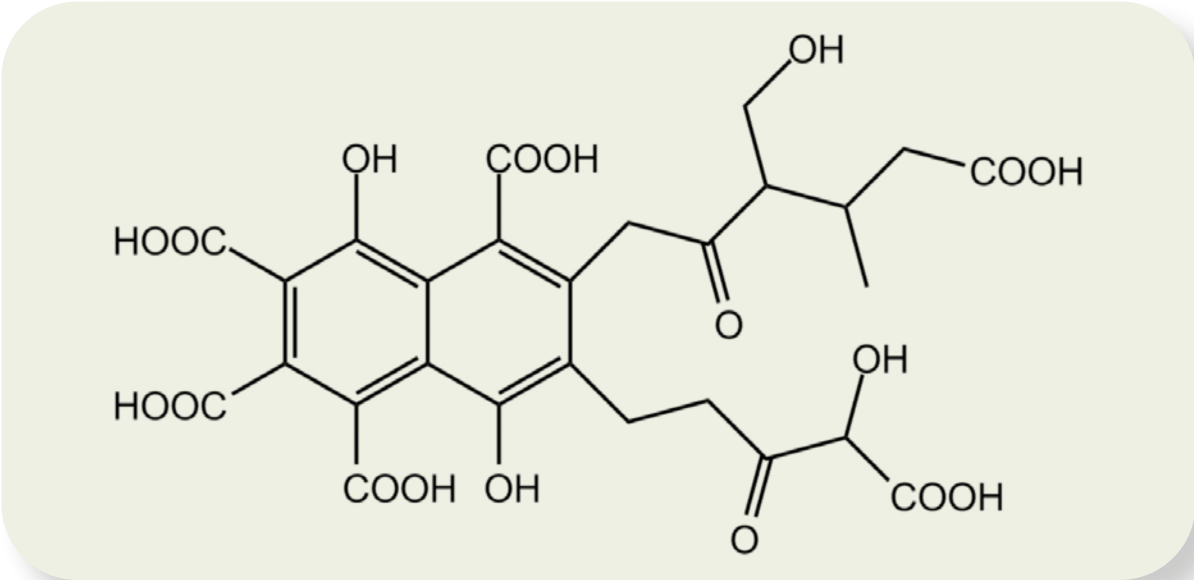


Figure 4 - A fulvic acid

These humic substances form relatively homogeneous classes of compounds despite the wide diversity of material from which they originate.

Humus constitutes all of these materials and organic substances; it is the final product from their decomposition and conversion caused by several biological agents present in the soil (the biomass, consisting of bacteria, living fungi, crustaceans, insects, nematodes, earthworms, etc.).

Humus consists of molecules that provide **physical and exchange roles** in the soil. It has very little involvement in nitrogen transfer. It accounts for approximately 60–80% of total organic matter. Stable humus represents 15–30% of total humus, and consists of short life-cycle organic molecules (nutrient reserve). Humus is found in the soil's surface layer (especially in the superficial horizons O and A).

Factors affecting the speed and quality of decomposition

The rate of humus formation and mineralisation in the soil depends on a number of factors. In a hot climate, microorganisms are more active and organic matter decomposes more rapidly. The degree of soil acidity, the composition of organic matter, humidity and the availability of oxygen also have a significant influence on the rate of decomposition.

Three types of factors can influence the rate and quality of decomposition, and therefore the formation of humus.

1. **Environmental factors:**
    - aeration
    - temperature
    - humidity
    - soil or substrate pH
    - presence of any inhibitors that hinder the metabolism of decomposers (heavy metals, biocides, etc.).

2. **Factors related to the quality of organic matter introduced into the system:**
   - size and shape of organic residues
   - carbon (C) to nitrogen (N) ratio of the soil's organic residues as a whole. The C:N ratio is an index that determines the degree of evolution of organic matter, that is, its ability to decompose more or less rapidly in the soil. The C:N ratio is very high for fresh plant material (50–150 for straw) and decreases throughout its decomposition, stabilising at around 10 for humus. It is commonly accepted that the higher a product's C:N ratio, the more slowly it will decompose in the soil, but the more stable the resultant humus will be. This index is used to specify the use of an unknown organic product. For optimal composting, the C:N ratio must be between 15 and 30. If the mixture to be composted is too low in nitrogen, it will not heat up (there will be no degradation). If the nitrogen content is too high, the compost can overheat and kill the compost's microorganisms. The inputs must therefore be balanced (see Table 3).

Table 3: Carbon to nitrogen ratios

C:N < 15	As nitrogen is produced, the speed of decomposition increases; it is at maximum for a C:N ratio of 10
C:N 15–20	Nitrogen requirement met, to allow a good decomposition of carbonaceous material
C:N > 20	Not enough nitrogen to enable the decomposition of carbon (there is competition between absorption by plants and the reorganisation of the organic matter by the soil's microorganisms; this is the 'nitrogen hunger' phenomenon). Nitrogen is then taken from the soil reserves. Mineralisation is slow and only returns a small amount of mineral nitrogen to the soil.

3. **Factors related to the composition of organic matter**, which influences its rate of decomposition. This varies depending on the proportion of the following compounds, presented in order of decomposition from fastest to slowest:
   - sugars, starches and simple proteins
   - hemicellulose
   - cellulose
   - greases, waxes, oils, resins
   - lignin, phenolic compounds, chitin, etc.

Properties of humus

Humus is the most biologically active part of the soil's biosphere compartment. Sometimes called topsoil, humus is the upper layer of the soil, created and maintained by the decomposition of organic matter, mainly through the combined action of animals, bacteria and soil fungi. Humus is a soft, airy material that absorbs and retains water well. Other sections will discuss which organisms live in the soil, and their role in soil structure and fertility.

Humus has the following properties (Inckel *et al.*, 2005):

- improves soil structure
- improves the soil's resistance to the erosive action of rain or wind
- can retain water and slowly release it to plants (water storage capacity)
- can retain nutrients from the soil and slowly release them to plants
- contains important nutrients: nitrogen, phosphorus and potassium, which will be available to plants after decomposition. Slow and natural decomposition of a humus soil releases the nitrogen, phosphorus and all nutrients essential for plant growth directly to the plant roots. The raw material of humus is litter, to which is added components of animal origin deposited on the superficial horizon or introduced by burrowing animals, including earthworms.

Humus plays a major role in the fertility and water-holding capacity of soils. Its formation and conservation in the soil are therefore a priority for maintaining fertility in a sustainable way.

Humification agents

The soil's **flora** (bacteria, fungi) and **fauna** (woodlice, ants, collembola, earthworms, slugs, myriapods) fragment and transform plant and animal residues. Humification agents operate by turns in a complex trophic network that is still little understood. The biological properties of soil, and the crucial role of the many organisms living in and on the soil, are discussed in more detail further (see Figure 5).

Soil flora and fauna are mainly microorganisms that directly decompose part of the humus into carbon dioxide (CO_2), water and nutrients, making them available for plants. This process is called **mineralisation**. Mineralisation releases nutrients that can be directly assimilated by the plant roots.

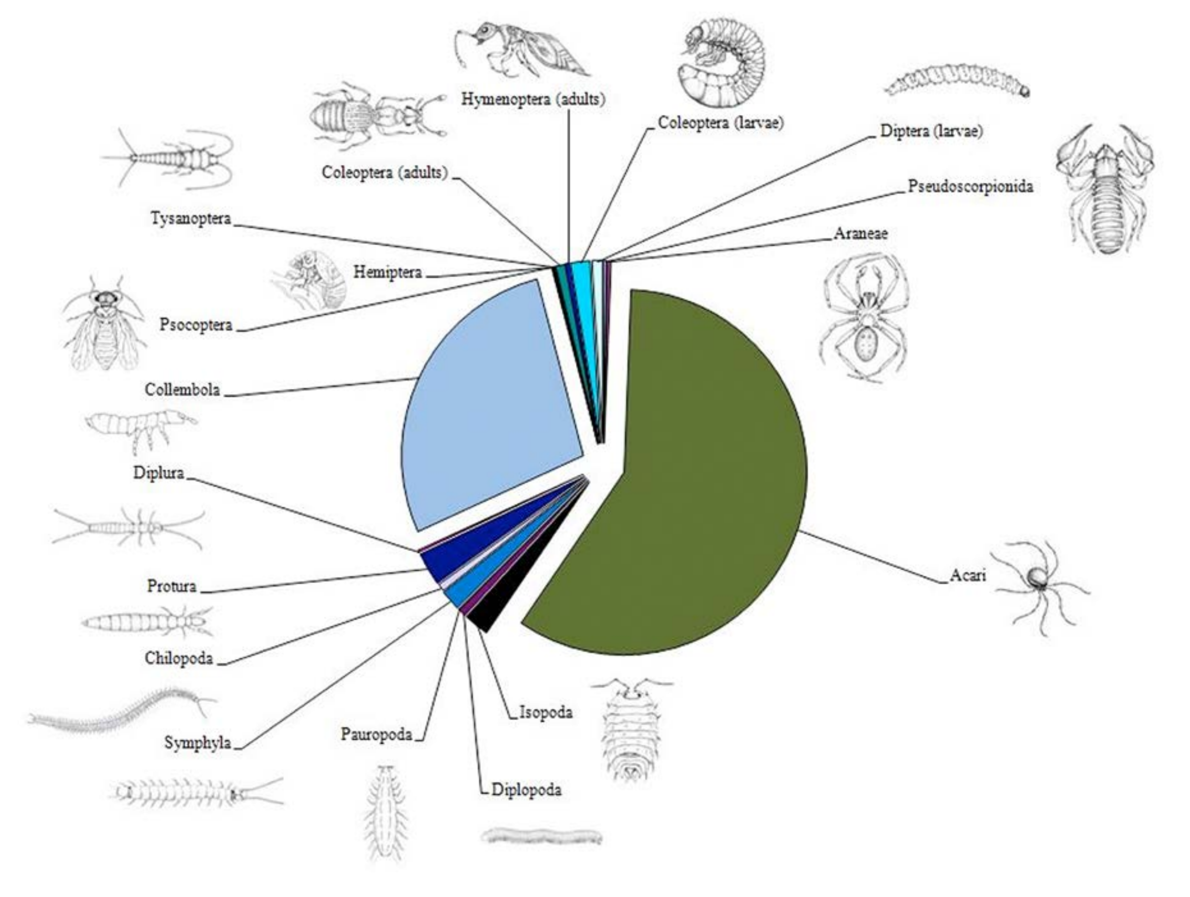


Figure 5 - Soil fauna
Source: Cristina Menta (2012)

Soil flora

Algae: many autotrophic algae (which possess chlorophyll) are located mostly in the first two cm of soil. These algae fix CO_2 and turn into organic matter when they die they, so a small amount of organic matter found in soils comes from autotrophic algae. But most algae found in the soil are heterotrophic and live in the deeper layers, **degrading organic matter**. Algae produce a mucilage that surrounds them and that harbours many bacteria.

Bacteria: the role of bacteria is very important in **humification** processes. With regard to soils, one of the main distinctions between bacteria is their distribution between aerobic and anaerobic organisms.

- **Aerobic bacteria** are predominantly involved in humification. They proliferate in environments that are rich in nitrogen and have a low acid content; they are mostly abundant around the roots of certain plants (grasses, leguminous plants), within the rhizosphere.
- **Anaerobic bacteria** also play a role during wet periods of the year or in poorly ventilated microsites of a ‘normal’ soil. Anaerobic bacteria are mainly involved in the processes of peat formation and putrefaction.
- Most are **heterotrophic** and **saprophytic**; they decompose cellulose and sugars, which represent sources of energy and are for the most part mineralised as CO_2.

- Certain more specialist bacteria are **autotrophic**: they derive their energy from the oxidation of certain compounds (sulfur, ammonia, ferrous iron, etc.) and assimilate carbon from CO_2.

Fungi: these are more resistant than bacteria to drought and acidity, and constitute the almost exclusive microflora of certain dry and acid mors. But unlike bacteria they are always heterotrophic and aerobic; they do not proliferate in poorly ventilated environments. Their role in the soil is considerable and varied. They are mainly involved in the **decomposition** phase of the fresh organic matter that precedes humidification: most can decompose cellulose, and some can decompose more resistant phenolic compounds such as lignin and tannins. Some fungi are associated with the roots of plants and trees, forming **mycorrhiza** that live symbiotically and facilitate the growth and nutrition of the species concerned.

Actinomycetales: these are intermediate soil microorganisms between bacteria and fungi. Actinomycetales are important in the **decomposition** of litter and **humification**. They appear to play a large role in the conversion of certain organic and soil mineral compounds, but this role is still poorly understood. They are thought to be capable of decomposing the compounds of fresh organic matter such as lignin and certain tannins, and developing certain humic acids. Actinomycetales also have other functions: some species, *Frankia alni* in particular, form nodules with the roots of alders and trigger an active fixation of atmospheric nitrogen, which explains the beneficial role of this species.

Soil fauna

The soil fauna is divided into micro-, meso- and macrofauna, according to the size of organisms. Figure 6 illustrates the fauna found most frequently in the soil.

- **Microfauna** (<0.2 mm) consist mainly of protozoa and nematodes; they are abundant in very humid environments, and attack bacterial flora and actinomycetales.
- **Mesofauna** (0.2–4 mm) are mites and collembola that mainly characterise acid environments; also includes some nematodes.
- **Macrofauna** (>4 mm) include earthworms, which play an essential role in structuring A horizons of active mull earths with low acidity; Enchytraeidae (another class of worm), which are mainly found in acid environments; and insect larvae (diptera, beetles). They are more abundant in acidic and dry environments.

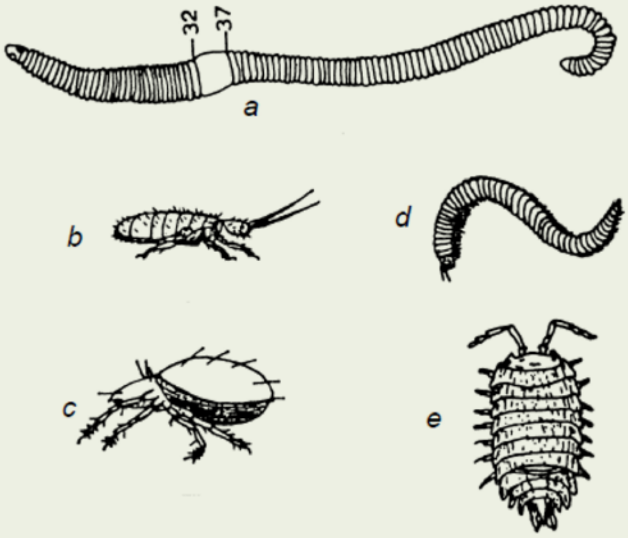


Figure 6 - *Soil organisms: a) earthworm; b) collembola; c) mite; d) millipede; e) woodlouse*

The structure of the soil depends on the assembly of the mineral and organic particles into aggregates, which themselves can form clods. This structure is built by the 'soil engineers' (earthworms, termites, etc.): macrofauna that aerate and stabilise the soil, and enable good water circulation. Ants, termites and earthworms also work the organic matter, each shaping the soil in their own way by burrowing, scratching, mixing, turning or ploughing it. They create numerous pores, tunnels and aggregates that allow better oxygenation of the soil and maintain its hydraulic properties (such as water infiltration and retention).

A termite mound, consisting of soil, manure and termite saliva, can take four to five years to build up, and it evolves continuously over time. Like ants, termites are social animals, and erect these impressive structures, sometimes more than 5 m tall, as a group. Although the mound may appear solid, it is actually porous to allow air to circulate through the tunnels and chambers. The air enters the mound through tiny holes and oxygenates the structure. As it heats up, the air rises and leaves the mound through the central chimney. This unique ventilation system maintains a constant temperature inside, where the termites reside, rear their larvae and store their food, and even cultivate a symbiotic fungi farm for food. By promoting the penetration of rainwater, termites create pockets of humidity in dry soils. The surrounding vegetation will then survive for longer during periods of drought and enable plants to recolonise the surrounding area when the rains return. **Termites are pivotal to ecosystems' resistance to desertification** (Kelly, 2015; Figure 7).

Figure 7 - Termites in the Atacora region of Benin
Source: Rovillé (nd)

The work of earthworms is equally important: they can work 1,000 tonnes of soil per year, per hectare of African savannah (500–600 tonnes in temperate regions), which substantially increases the quantity of water in the soil. Interacting with the macrofauna, the work of microorganisms, small fauna, fungal filaments and roots, which move and organise mineral (clays, silts, sands) and organic particles, is also considerable (Rovillé, nd).

1.1.3.5. Soil colours

The first thing you notice when looking at soil is its colour. The three main soil colouring agents are:

- organic matter: black or brown
- **iron**, through its oxides in the broad sense: red, purplish, rusty brown in oxidising mediums, bluish or greenish in a reducing environment
- **limestone**: white.

Darker colours on the surface are an indication of soil fertility. Black soils are generally more fertile than soils that have a lighter colour, because they contain a higher percentage of organic matter. The colour of organic matter is darker (brown to black) than that of iron oxides (yellow, red, brown). This colour generally dominates in the surface horizons, while in the lower horizons the colours of iron oxides (red) and sometimes manganese oxides (very black) dominate.

Some soils have a colour that is directly inherited from the rock from which they originate. For others, the colour is due to the constituents that have been accumulated or concentrated during soil formation (weathering complex and organic matter).

Changes in colour can also give an indication of the soil's water regime: the colours of iron oxides under dry and aerated conditions are different from those under flooded conditions.

Figure 8 shows an example of moderately differentiated fersiallitic soil. This type of soil is generated by a sub-humid tropical climate. The parent rock (not visible in the photo) is basalt. We can distinguish the following horizons:

- an A horizon, organo-mineral, dark coloured
- an S horizon, with weathering to the soil structure, red (well drained), with well developed angular (polyhedral) structure; the texture is clayey (probable presence of swelling clay)
- a C horizon, resulting from weathering of the bedrock.

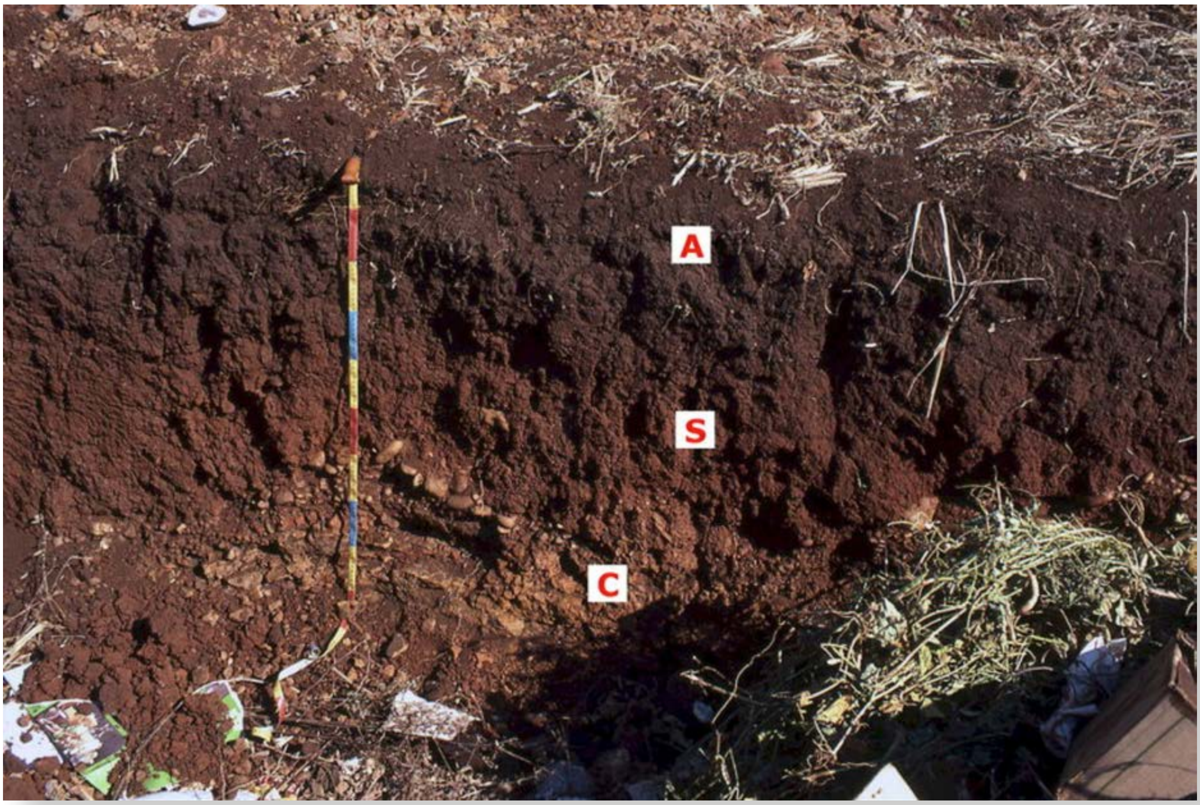


Figure 8 - Typical example of a coloured soil, with three distinct horizons[3]
Source: AFES photo library

Figure 9 shows the colours of two weathering profiles. In these examples, the O and A horizons have disappeared; the S horizon is a weathered horizon; rm is the parent rock (*roche mère*) thus bed rock (unweathered rock at the base of the profile; the origin of the soil).

3 Phaozem (WRB, 2015).

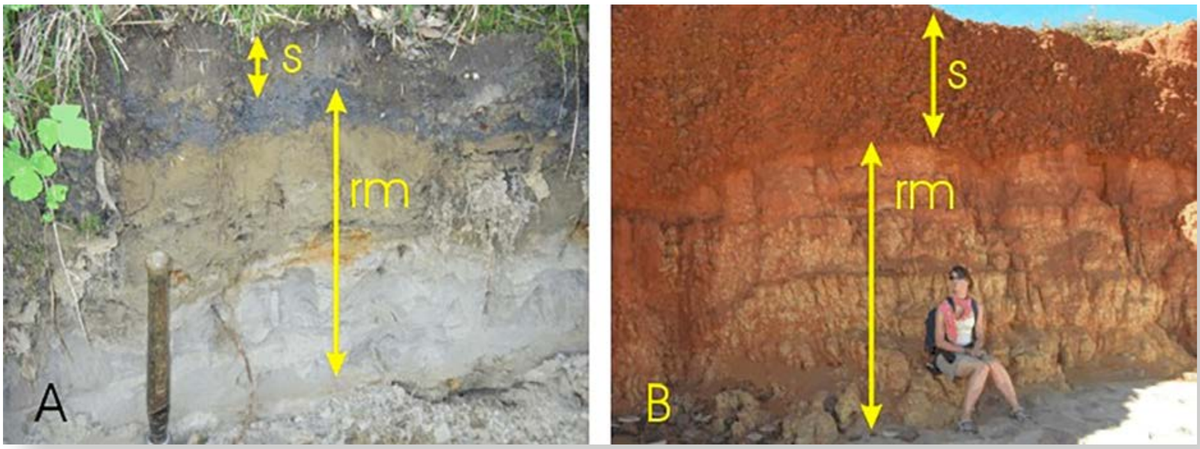


Figure 9 - Examples of two weathering profiles
Source: University of Liège

Profile A is a temperate climate soil (Habay, Belgium) that tops sands and clays, above the parent rock.

Profile B is a soil from a tropical climate, a weathering horizon above the parent rock. Here the red colouring of the S horizon is due to the accumulation of iron hydroxides.

1.2. SOIL FORMATION AND SOIL TYPES

1.2.1. Soil formation (pedogenesis)

1.2.1.1. Major processes of soil formation

Soil takes a very long time to form (several thousand years). Under certain conditions, the parent rock (the mineral element) is weathered by air and water, which makes it possible for the first pioneer plants to establish themselves. Then the organic matter from dead plants and animals forms a litter on the surface. This is decomposed by the soil fauna and converted into humus, then mixed with mineral elements, becoming cultivable soil; this is what is called arable land. It is important to understand that soil formation processes can evolve and vary with topography and time, in response to factors such as climate variability and land use for human activities (e.g. the difference between pasture and cropland).

Figure 10 illustrates the main soil formation processes. The dark colour of the upper part of this soil profile indicates that significant quantities of organic matter have accumulated in the arable layer through decomposition of vegetation and roots. The lighter colour between 20 and 40 cm is due to a combination of leaching of the mobile iron and loss of clays through percolation of rainwater. In the subsoil, the iron has coated the soil particles with a thin, reddish film. The parent rock from which the soil has developed and the weathering front are clearly visible at the base of the profile. Biological processes are generally more active in the arable layer.

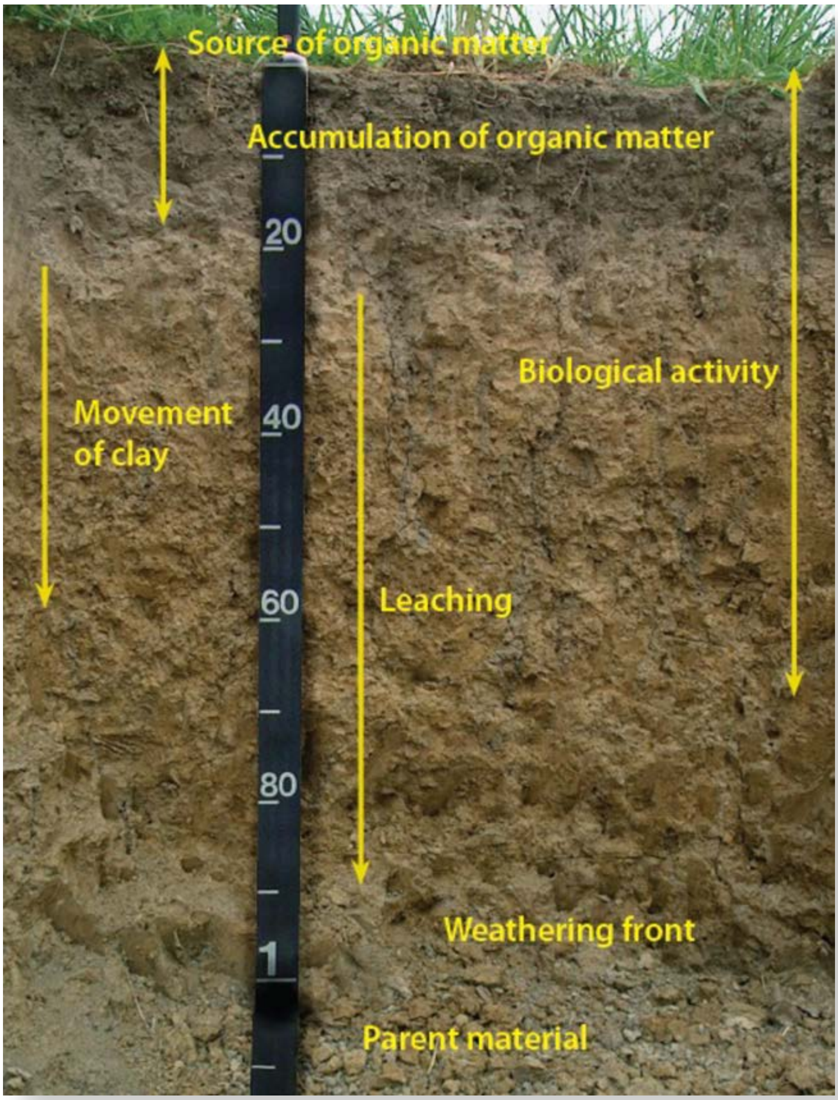


Figure 10 - Main processes of soil formation
Source : Jones *et al.* (2013)

The formation of a soil involves several processes, including:

- disintegration and alteration of parent rock (weathering)
- enrichment of the soil by organic matter (accumulation and incorporation)
- migration of substances and particles into the soil profile (leaching of soluble elements and particle movements).

Disintegration and alteration of parent rock (weathering)

All soil comes from the decomposition of rock, which for this reason is called parent rock. This can be either a hard rock (volcanic rocks and hard calcareous rocks) or a soft rock (soft calcareous rocks, marls and compact clays, sands, scree and loess). All sediments are derived from the solid rock following a process called weathering. Weathering is defined as the mechanical destruction of the rock's structure, which then triggers chemical changes in its constituent minerals.

Natural weathering brings together all the mechanical, physicochemical and biological processes of elementary reduction of rocks and minerals on the surface of the Earth. It fragments the material without altering its nature, and the rocks are gradually reduced to increasingly fine particles. At the same time, the water and energy present in the soil cause chemical reactions that alter the initial (primary) materials and produce new (secondary) minerals. Thus the original material is gradually fragmented and weathered to result in a material that is a mixture of the original constituents and new minerals, for example clays, which play a very important role in soil fertility. The original material may be a rock (parent rock) or an unconsolidated material (alluvial deposits, colluvium, loess, glacial deposits).

The intensity of the physical disintegration and chemical alteration depends on the climate, which is the driving force behind soil formation. In most ACP countries, the alteration of rocks that leads to soil formation is more complete and more rapid due to high temperatures. The weathering index is about three times higher in a tropical than in a temperate climate, which partially explains altered layer in tropical environments.

Water is the key factor in chemical weathering. Since rainwater is slightly acidic (pH around 5.6 in unpolluted environments), naturally soluble minerals (e.g. gypsum, chalk) or those that are unstable (e.g. feldspar, mica) will slowly dissolve to form secondary products such as clay (e.g. kaolinite, illite, vermiculite), iron and aluminium hydroxides, carbonates, and nutrients such as calcium and potassium. A series of chemical reactions (oxidation and reduction) cause the release of various cations in the soil.

The effects of the activities of **living organisms** are combined with these two forms of weathering: physical and chemical. The roots of plants then develop in fissures and burst through the rocks; bacteria and fungi convert the organic matter; while animals such as earthworms, ants and termites dig tunnels and mix or turn the soil.

The first result of these alterations and weathering is a **mixture** of minerals of varying degrees of disintegration, but not yet altered, including boulders of stone and gravel, and grains of sand and silt powder. It then forms a kind of paste, the **weathering complex**, derived from the chemical alteration of minerals including a clay paste, coloured by iron oxides and calcium, magnesium, potassium and sodium salts in varying soluble states.

Soil enrichment by organic matter

Soil is created only when the **mineral constituents** are added to the **organic constituents**, that is, the organic matter derived from animal and plant organisms. From that point, which occurs at the very start of weathering, organic debris (particularly plant debris) results in the formation of black substances with varying degrees of paste, grouped under the name humus. These substances influence the soil's fertility and, in combination with climate agents, play a major role in the soil's subsequent evolution.

High temperatures also have an effect on the dynamics of the organic matter – mineralisation of organic matter accelerates, leading to a rapid depletion of humus in the soil when natural vegetation is replaced by crops that do not allow for sufficient return of organic matter to the soil (e.g. from crop residues).

Migration movements downwards and upwards

In a young soil that is continuing to deepen, the downward and upward **movement of water** causes the colloidal (clay, humus) and soluble (calcium salts, iron oxides, etc.) elements to undergo displacements, referred to as migrations (see Box 2).

- **Downward** movements predominate in climates with high rainfall, and involve lixiviation[4] of elements and leaching of particles (e.g. clays). The rate of percolation depends on the climate, as well as the soil's texture and structure, and the porosity and slope of the terrain. In dry regions, even the most mobile compounds (e.g. sodium chloride) tend to remain on the surface layer, leading to the formation of saline soils.
- **Upward** displacements, or creep (e.g. of dissolved salts), dominate in climates with high levels of evaporation. These movements are responsible for the phenomenon of soil salinisation, which is extremely damaging to soil fertility (see Chapter 4).

When the water passes through the soil, it dissolves the **soluble salts** (chlorides, nitrates, sulfates and carbonates) and carries them, together with organic and chemical solutions, towards deeper sections of the soil. In dryer climates, these salts can be re-precipitated, for example in a horizon that is rich in calcium carbonate in the subsoil. In more humid areas, large quantities of materials can be completely removed from the soil through lixiviation. These migrations are also at the origin of the formation of leached or depleted horizons, and of accumulation horizons of clay, humus and/or iron oxide (Soltner, 2005).

The intensity of these migrations depends on several factors, including **rainfall**, as well as the capacity of the clay–humus complex to retain the elements (absorbency, or **retention capacity**). A specific feature of tropical climates is their high rainfall intensity and, in monsoon regions, high rainfall concentration over a short period. In rainy regions, where infiltration and deep drainage are significant, there is considerable risk of lixiviation of nutrients. In cultivated areas, this process is aggravated when cultivated plants are shallow-rooted and incapable of raising to the surface bases that have been carried deeply downwards through natural drainage.

i

Migration affects pH and thus soil fertility

The phenomenon of dissolving/migration is an important factor for soil fertility. Where calcium carbonate is present, the soil's pH is greater than 7 (see Chapter 3). When calcium carbonate is dissolved and carried more deeply, the pH falls, and calcium, magnesium and sodium are released from the surfaces of the clay minerals and humus to be replaced by hydrogen and aluminium. This causes the soil to become acidic. Soils that are too acidic are not well suited to crops because at a pH less than 5.5 aluminium cations toxic to plants are released into the soil solution. It is then necessary to add calcium carbonate (liming) to increase the pH to a level that is suitable for cultivation.

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4 In agriculture, 'lixiviation' refers to the loss of water-soluble nutrients from the soil, which are dissolved and carried away by infiltration water following rainfall or irrigation. Some also call this 'leaching'.

1.2.1.2. Six elements involved in soil formation

There are six elements involved in soil formation:

- composition of the bedrock (the parent material that will be altered)
- climatic conditions (the climate is the driver of change)
- living organisms: vegetation and other (micro)organisms
- time (duration of events)
- topography
- human interventions (crop practices; also fires, deforestation, etc.).

The first four elements are the most important. The influence of certain cultivation practices and human activities on the soil (degradation, deforestation, salinisation, compaction, pollution) are covered in following chapters.

Original material

The nature of the parent material (its composition, but also whether it is a loose or hard rock) can have a profound influence on the characteristics of the soil. For example, the texture of sandy soils is mainly determined by their parent materials, and this controls the movement of water in the soil. The mineralogy of the parent material is reflected in the soil, and can determine the weathering process and control the composition of the natural vegetation. For example, carbonate soils are generally derived from calcareous rocks (limestone, chalk) or sediment from deposits of this kind (Jones *et al*., 2013).

Water is the main weathering agent of the original material. Several factors are involved: the weathering of the bedrock varies with temperature (governed by climate, exposure and altitude), the rate of percolation (governed by texture, depth and climate), the presence of oxygen (governed by texture and climate), the mineralogical composition of the parent material (e.g. quartz is much more stable than olivine), and the production of organic acids. The minerals of heavily weathered soils in humid/tropical regions are very stable (e.g. kaolinite).

Climate

The formation of soils is heavily dependent on climate, as temperature and humidity levels affect the weathering processes. Soils may be leached or saturated with water when precipitation exceeds evapotranspiration; when the reverse is true, salts may rise to the surface. Chemical weathering will be very active in areas where temperature and humidity levels are high, while physical weathering will dominate in hot and dry desert regions.

Climate also has an obvious influence on living organisms, although the (micro)climate observed on the surface of the soil may be very different from the regional climate. This microclimate can be subject to topography, which itself is the result of the interaction between the underlying geology (in most cases, the parent material) and the local climate.

In relatively warm countries where the temperature never falls below zero, natural weathering (fragmentation of the bedrock without chemical weathering) is much less significant (since no frozen water penetrates into the crevices of the rock).

The absorption of water on the surface of certain types of rocks causes clay minerals to swell, while drying then makes them contract. It is therefore a process of swelling and contraction that fragments the rock. This is very common in marls, where the effect is accentuated by dissolution of the calcite present in the rock.

The main types of soils are distributed globally according to two climatic factors:

- the average temperature of the region;
- and the general humidity of the climate in the region (see Table 4).

Table 4: Distribution of soil types according to climatic conditions (Note that this document does not address boreal climates and the specific soils that form there, such as chernozem or podzols.)

<table>
<tr><th>Climate</th><th colspan="4">Increasing humidity gradient →</th></tr>
<tr><td>Temperate</td><td>Brown soils</td><td>Chestnut soils</td><td>Brunizem</td><td>Burnished soils</td></tr>
<tr><td>Subtropical</td><td>Dark brown soils</td><td rowspan="2">Fersiallitic soils</td><td colspan="2">Ferruginous soils</td></tr>
<tr><td>Tropical</td><td>Tropical red-brown soils</td><td></td><td>Ferrallitic soils</td></tr>
</table>

Accumulation of Ca^{2+} ⟷ Increasing losses of Ca^{2+}

Source: adapted from Duchaufour, 2004

The reality is more complex because there is also an influence of seasonal variations (e.g. alternating dry and wet seasons, sometimes several times during the year), which have a major impact on soil formation, for example on the maturation of humus or the leaching of elements.

Living organisms

Fauna and flora (from microorganisms to humans) affect soil formation. Living organisms add organic matter, an essential component of soils, by decomposing litter and roots. **Microorganisms** such as fungi and bacteria facilitate root-to-soil exchanges and make essential nutrients accessible to plants. Fauna and flora allow moisture and gases to penetrate deeper into burrows and root canals. Humans can influence soil formation through their land management practices, which disrupt natural processes and alter the physical and chemical characteristics of the soils. Agricultural practices and burrowing animals mix the soil from different horizons, especially the surface layers that are rich in organic matter (Jones *et al.*, 2013).

Plant types and surface biomass are highly correlated with climate. **Vegetation** contributes organic matter to the soil, and organisms decompose the organic matter and structure the soil. Plants favour the natural weathering of the original material through root penetration. The decomposition of organic matter rich in carbon, hydrogen and oxygen releases hydrogen ions that promote chemical soil weathering.

The presence of plants (and colonisation of the soil by roots) plays an essential role in soil formation. Desert environments devoid of plants have very little soil differentiation, unlike environments with dense plant cover.

Time

Time allows the soil to form horizons that reflect local conditions. As noted above, the timescale for soil formation is measured in thousands of years. However, this should be considered in relation to the intensity of natural weathering: hundreds of millions of years in an arid environment may produce effects that are less significant than those of a few hundred years in a tropical humid environment. The more intense the natural weathering and soil formation conditions, the less time it takes to alter the original material and form distinct horizons.

1.2.2. Soil types

There are huge variations in soil type that only soil scientists are able to recognise and describe. This handbook focuses on describing a few representative soil types that are most often encountered in ACP countries (apart from desert soils, not discussed here because they are unsuitable for cultivation).[5]

1.2.2.1. Light brown soils

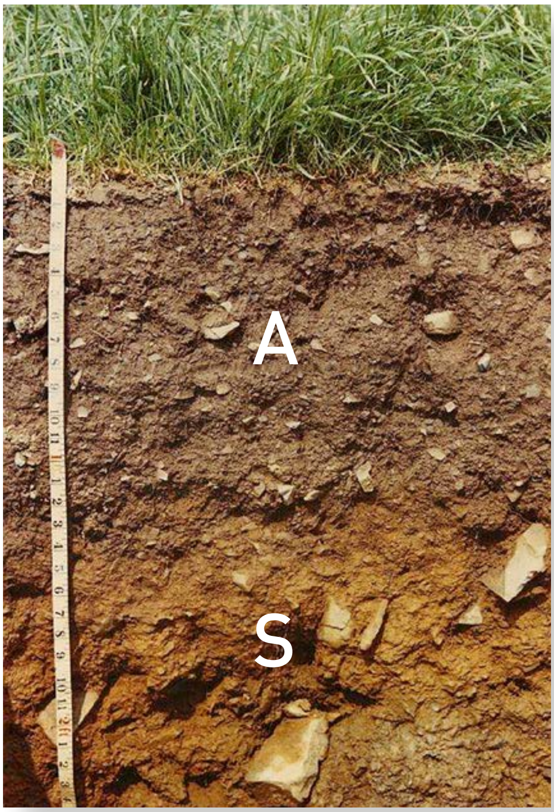
Light brown soils (Figure 11) develop mainly on forest soil climaxes as well as on siliceous and calcareous soils.

These are the soils that provide the best agricultural land.

- **The upper A horizon** is organic and mineral. It may be leached to varying degrees. Depending on the nature of the bedrock, the humus may be a mull (base-rich soils and/or soils rich in active calcium); a moder (base-rich soils, siliceous bedrock); or a mor (siliceous rock or clays, base-poor soils, acids).
- **The S horizon** is the weathered or structural horizon.
- **The C horizon** is the parent rock.

When light brown soils are weakened (e.g. due to a lack of humic or calcium soil improvers), they become more susceptible to **leaching**, where the soil becomes **acidified** and **slaked** on the surface (i.e. there is a tendency to form a crust on the surface due to the effect of rain). This depletion in organic matter or calcium is accelerated when farmers neglect to practise crop rotation (or simply add herbicides), do not lime, or support plant growth purely through application of chemical fertilisers. For example, intensive monocropping of maize is extremely impoverishing for light brown soils.

5 For soil vocabulary and nomenclature, refer to works such Duchaufour, P. (2004) and '*Pedological repository*' (Quae, 2008).



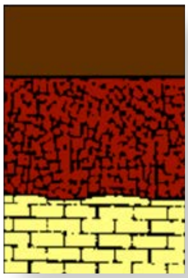


Figure 11 - Soil profile of a typical light brown soil (horizons A and S)

1.2.2.2. Ferruginous and fersiallitic soils

Ferruginous soils are formed mainly in regions where there is a very long dry season and a grassy savannah soil climax (e.g. in parts of tropical Africa). The soils of semi-arid regions experience initial chemical weathering. Leaching is minimal, due to the short duration of the rainy season. The result is **light, loose, sandy** soils (Figure 12).

In ferruginous soils, the A horizon consists of a thin A1 horizon, rich in organic matter and minerals, above an eluvial A2 horizon. The B horizon is enriched with clay colloids brought by leaching (specialists call it Bt). These soils are rich in iron and clay (kaolinite), but are almost (or totally) devoid of free aluminium. While these soils are not very sensitive to human activities, the same is not true of their original vegetation cover, which, following slash-and-burn cultivation, is likely to become deeply and permanently depleted.

Fersiallitic soils are also called red soils. They are the result of a strong and stable association between clay colloids (montmorillonite) and iron oxides. Mediterranean terra rossa are red soils rich in aluminium oxides that formed when these regions had a tropical climate. These soils are generally **rich and fertile**, with stable or not very mobile humus. But they are fragile soils, particularly sensitive to wind or water **erosion**, especially where vegetation is stripped if the soil becomes exposed after a fire or following overgrazing. Erosion reduces these soils to skeletal soils around sterile calcareous crusts.

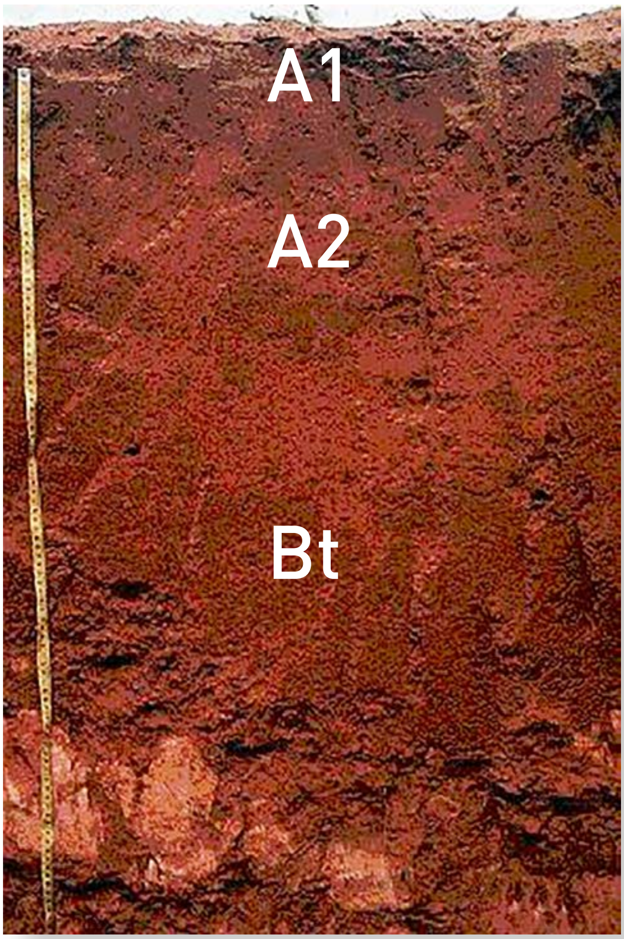


Figure 12 - Lixisols: classified as leached ferruginous soils (not very acidic)

1.2.2.3. Ferrallitic soils

Ferrallitic soils are red soils typical of humid tropical climates. They are rich in iron oxides and aluminium oxides. These soils form under forest cover in tropical or equatorial climates. They are very fertile but extremely fragile.

Ferrallitic soils are particularly sensitive to wind and water **erosion**, especially where vegetation is stripped after a fire or following overgrazing. As soon as the forest cover that protects against erosion, leaching in particular, is removed, these soils rapidly convert into crust as a result of laterisation. Iron oxides and colloidal aluminium precipitate to form nodules (iron pan), which if bound together form the completely sterile ironstone.

The horizons are as follows: A, red, slightly organic; E, light red, slightly depleted in clay; and Sk, red, sandy clay, weathered soil structure, rich in kaolinite (Figure 13).

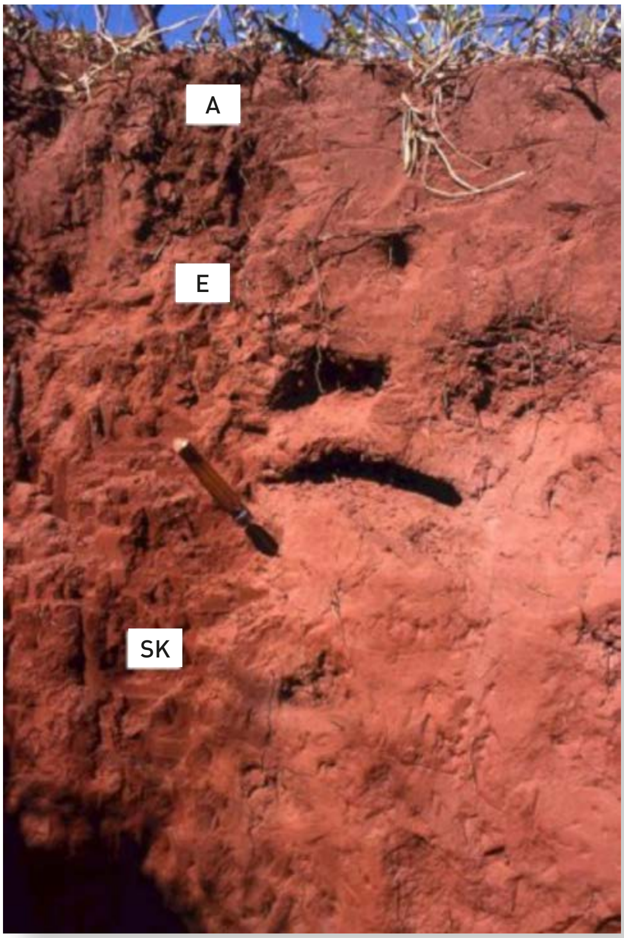


Figure 13 - Ferrallitic soil (highly differentiated leached soil)6

1.2.2.4. Saline and sodic soils

Saline soils have excessive concentrations of **soluble salts.** They contain various potassium salts (K^+), magnesium (Mg^{2+}), calcium (Ca^{2+}), chlorides (Cl^-), sulfates (SO_4^{2-}), carbonates (CO_3^{2-}), bicarbonates (HCO_3^-) and nitrates (NO_3^-). They are found mainly in dry regions.

Saline soils develop on rocks rich in sodium, calcium or magnesium, for example. The rocks may be naturally rich in sodium, or secondary rocks enriched with sodium from a salt water table of continental or marine origin. Secondary enrichment can also result from poor farming practices during which upwellings from the water table loaded with salts result in sterilisation of the soil. These salt upwellings have multiple causes; irrigation combined with high evapotranspiration is one of the most commonly cited. Saline soils are characterised by a simple profile with a somewhat thick single A horizon consisting of organic and mineral materials encrusted with precipitated salt deposits (Figure 14).

One example of a saline soil is sodic soils – also called **alkaline** soils – which have a structure that is conditioned by the sodium content adsorbed on the soil (Na^+).

6 Acrisol (WRB, 2015).

Figure 14 - A saline soil

1.2.2.5. Hydromorphic soils

Hydromorphic soils are found mainly in humid regions. They result from the continuous waterlogging of deep horizons, making them asphyxiating and reducing. The upper A1 horizon is a mixed organic and mineral horizon. Hydromorphic soils are generally predominantly **clayey**. Their structure is often heavy and compact, and can cause root asphyxiation of the crop and the death or slowing of microbial life.

The deep horizon is a gley or pseudo-gley. This horizon is characterised by asphyxial and reducing conditions, where iron in the divalent (ferrous) state gives a greenish colour. In the surface sealing zone of the water table that floods it, it is possible to observe zones where iron is in its trivalent (ferric) form and rusty in colour because it has been in contact with oxygen. The distribution of these ferric iron plates in the soil profile is a good indication of the extent of variation in height of the water table (Figure 15).

Figure 15 - A hydromorphic soil illustrating the typical colours

1.3. IMPORTANT PROPERTIES OF SOILS

1.3.1. Physical properties of soils

Texture or structure?

The soil's **texture** refers to the proportion of mineral particles of different sizes. The main classes of particle size are clay (<0.002 mm); silt (0.002–0.063 mm); and sand (0.063–2.0 mm). The texture can be estimated by touch between the fingers, and measured by sieving and sedimentation. Textural classes can vary by country.

Soil **structure** refers to the arrangement of soil particles (also called aggregates) and the spaces between them (pores). The structure is important for the movement of water and air, and for the development of roots (the soil's **porosity** is a key element to consider). The type of soil structure depends on biological activity, physicochemical and mineralogical characteristics, organic matter and soil management (agricultural practices including intensive or non-intensive use of chemical fertilisers and pesticides).

(Source: Jones *et al.*, 2013)

1.3.1.1. Soil texture

The texture of a soil is the **particle size distribution** of its constituents. This is the proportion between the small particles (clays), medium-sized particles (silts) and large particles, and sands with a diameter of less than 2 mm). Soil particle size analysis involves classifying the mineral elements of the soil **according to their size** and determining the percentage of each fraction. It determines whether a soil is **sandy, loamy or clayey**. Following international convention, particles are classified according to their diameter (Table 5).

Table 5: Particle size classification

Category	Particle type	Particle size
Fine earth	Clays	<2 µm
	Fine silts	2–20 µm
	Coarse silts	20–50 µm
	Fine sands	50–200 µm
	Coarse sands	200–2 mm
Coarse elements (skeleton)	Gravel	2–20 mm
	Stone	2–7.5 mm
	Rock	7.5–20 cm
	Boulders	>20 cm

The grouping formed by the clays, silts and sands form the fine earth of the soil, while the stones and gravel are the coarse elements (Figure 16).

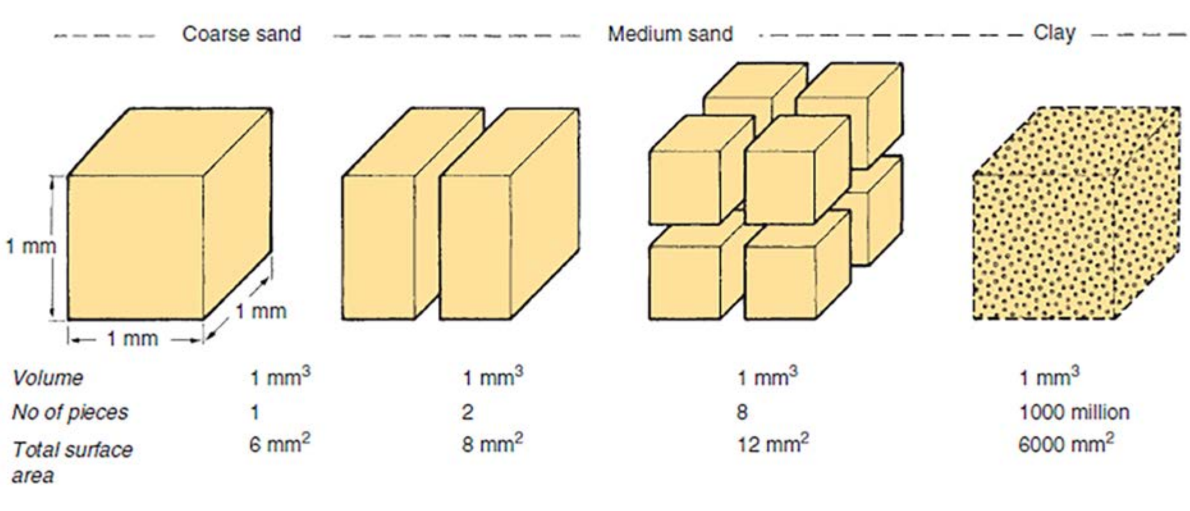


Figure 16 - The fine and coarse elements of soil

The classification given in Table 5 is represented by the **texture triangle** (Figure 17), the three sides of which correspond to the percentages of sand, silt and clay. When the percentages of these three major elements are rounded to 100% (excluding organic matter and rank patches, i.e. everything that cannot pass through a 2 mm sieve), the texture triangle can be used to determine the nature of the soil. The percentages of clay, silt and sand are found on the three axes. For each of the points found, a line is drawn parallel to the previous axis (e.g. for clay, the previous axis is sand). Each drawn line is parallel to one side of the triangle and intersects the two other sides. The intersection of the three lines designates the class of soil.

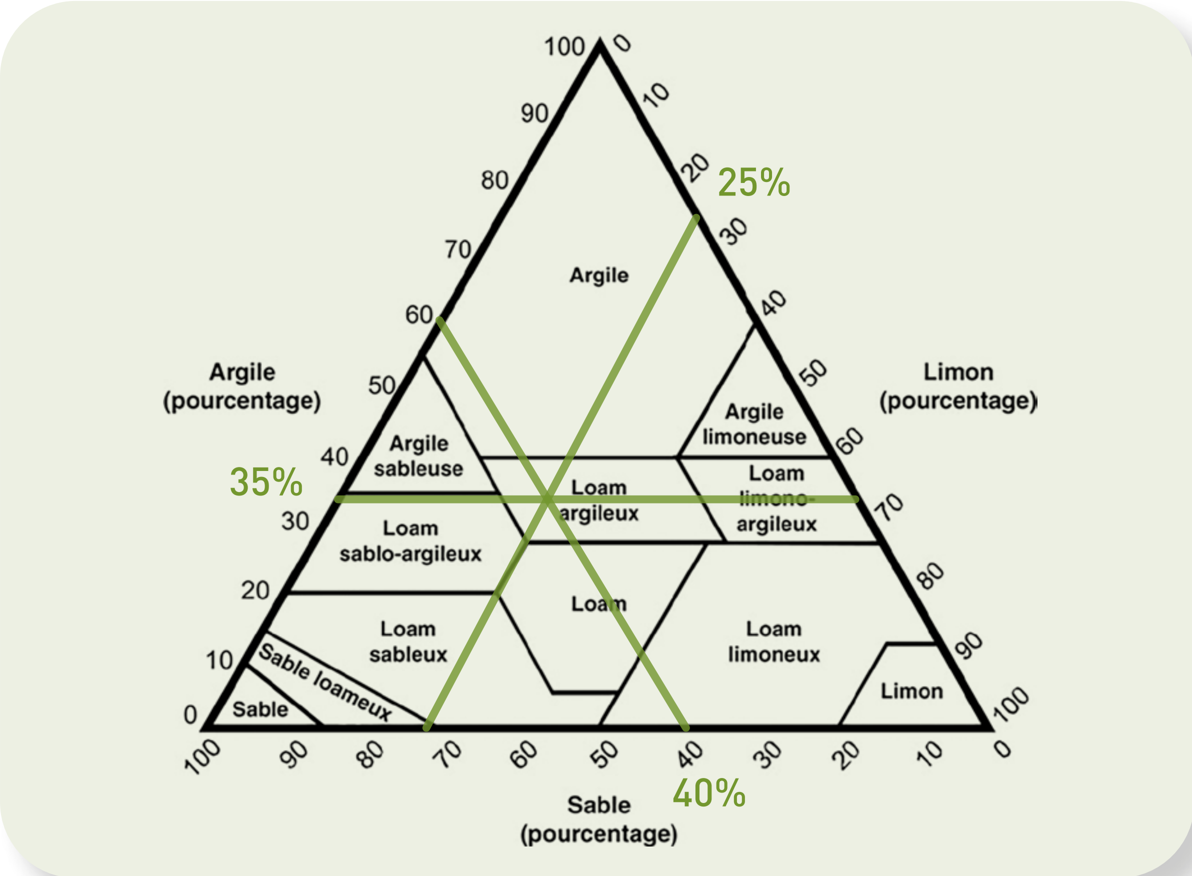


Figure 17 - The texture triangle for a soil with 35% clay, 25% silt and 40% sand

Four fundamental texture types define the main properties of soil:

1. **sandy** texture: well aerated soil, easy to work, low in water reserves, low in nutrients, low anionic and cationic exchange capacity
2. **loamy** texture: excess silt and insufficient clay can cause the formation of a massive structure accompanied by poor physical properties; this tendency is corrected by sufficient humus and calcium content
3. **clayey** texture: chemically rich soil but with very poor physical properties; impermeable and poorly ventilated medium forming a barrier to root penetration; difficult tillage due to high plasticity (humid state) or compactness (dry soil); a good structure favoured by humification partially offsets these unfavourable properties
4. **balanced** texture: this is the optimum as it demonstrates most of the qualities of the three preceding types without their faults.

Table 6 gives the soil classification criteria.

Table 6: Soil classification criteria

Soil texture	Sand (%)	Silt (%)	Clay (%)
Sandy	70 and over	0–30	0–15
Loamy	0–20	80 and over	0–15
Clayey	0–45	0–40	25 and over
Balanced	40–60	30–50	15–25

Knowing the texture makes it possible to indicate the soil's physical qualities:

- sand-rich soils are **permeable** and water filters through more easily, increasingly so with coarser sand
- if coarse elements are combined with fine sand and silt, they tend to clog the interstices between the coarse elements, making the soil more or less **impermeable**
- if sufficient proportions of clay are added to the silts and sands, especially in the presence of humus, a fragmentary structure may be created, guaranteeing **permeability** while **retaining enough water** for vegetation.

Field assessment of soil texture

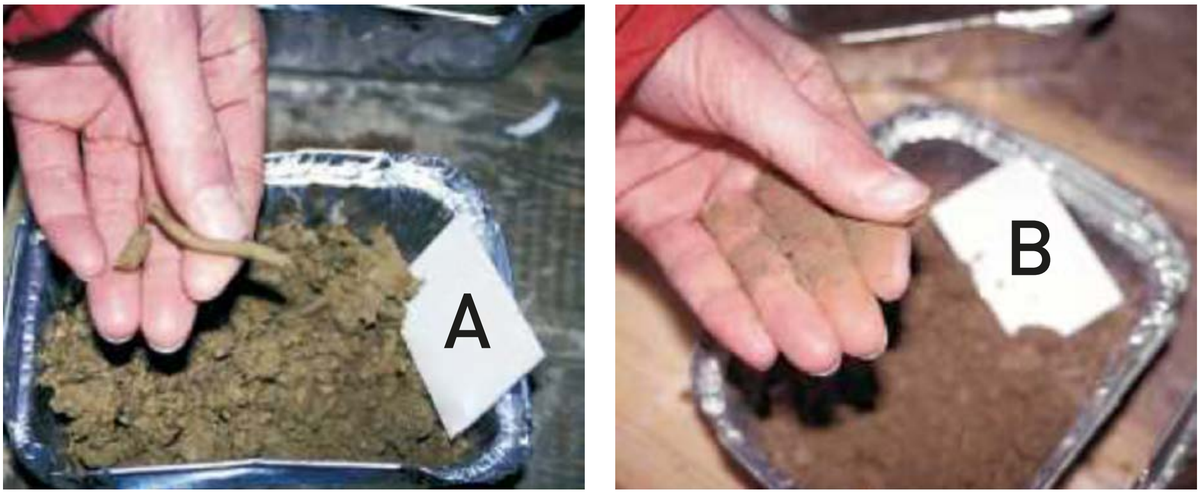
The tactile assessment of texture in the field can be performed by kneading a few cubic cm of fine earth (taken from the soil horizon to be tested) between the thumb, forefinger and middle finger (all coarse elements must be removed from the sample beforehand) (see Box 4).

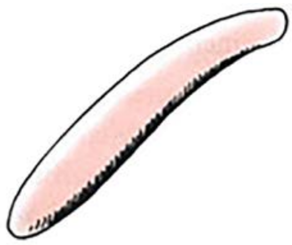
- **Clays** can be kneaded into dough-like pieces that do not crumble in the hand. The dough-like piece sticks to the fingers a little, and becomes very sticky if soaked with water; it is then possible to make a fairly thin roll (a few millimetres in diameter). The roll can be used to create a ring and does not break. In its dry state, clay forms very hard and highly cohesive blocks that do not stain the fingers, and become very difficult to moisten beyond 40% clay.
- **Sands** from 0.1 mm scrape under the fingers. If sands are dominant, it may not be possible to create a pellet or roll. Fine sands <0.1 mm do not scrape, but remain perceptible as a squeaking sound (a humid silty loam without sand does not squeak).
- **Silt-rich** soils feel smooth between the fingers; the dough-like piece is easily malleable and is crushed under low pressure. Larger rolls break up more quickly. In its dry state, silt is dusty and stains the fingers; small aggregates split off and crumble under the pressure of the fingers.

The roll test

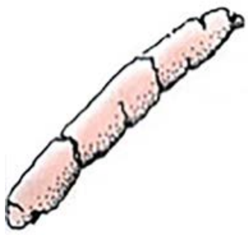
This test is used to determine the percentage of clay in a soil. To roll a sample of fine earth into a small sausage-shaped mass of 5–10 mm diameter, there must be sufficient (but not excessive) humidity to allow kneading. If it is too dry, add water. If the horizon is filled with water, mixing between the fingers causes rapid drying (Figure 18).

Roll cannot be created	<10–12% clay
Roll fragments once rolled in the palm of the hand	<18% clay
Roll does not fragment, but cannot be rolled into a ring shape	18–25% clay
Ring can be created and does not break	>25–30% clay

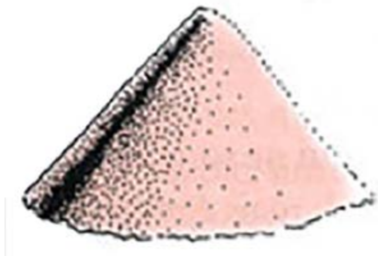




Soft, malleable roll:
clay soil



Fragile roll:
loamy soil



Unable to produce a roll:
sandy soil

Figure 18 - (A) Clay-rich soil: a roll can be formed; (B) silt-rich soil: stains the fingers

Laboratory assessment of soil texture

The texture of a fine earth sample is determined by particle size analysis. Various preliminary treatments (chemical and/or ultrasound) are applied to the sample to obtain good dispersion of the particles. These treatments are used to completely disaggregate the aggregates, which involves destroying the 'bridges' that make up the clay–humus complex. An initial treatment uses hydrogen peroxide to destroy the organic matter; a second treatment using dispersing salt is then carried out.

Knowing the texture indicates the soil's physical qualities. Soil texture has a major influence on the soil **moisture** regime:

- first, on the maximum **useful reserve** of each horizon, that is, the maximum quantity of water available to vegetation (e.g. it is well known that sandy soils have low water reserves)
- second, on the **circulation** of water in the soil – a sand-rich soil is permeable and filtering; a clay horizon can form a barrier to vertical infiltration of water.

- Texture also plays a role in **aeration** of the soil and its porosity: a sandy texture is a sign of a well ventilated soil, while a texture that is too clayey indicates an impermeable, poorly aerated environment forming a barrier to root penetration.

1.3.1.2. Formation of soil structure

The soil's structure is the way in which the particles are arranged on top of each other to form small clods. It refers to the size, shape and arrangement of the solid constituents (mineral and organic) and the gaseous constituents (voids); the continuity of the pores and their capacity to retain and transfer fluids and organic and inorganic substances; and the soil's ability to serve as a medium for root growth and development.

The **porosity** of the soil is defined as the ratio between the total volume occupied by the pores (voids) and the total volume (voids + plenums) of a sample (see section 3.2 for how to measure soil porosity). The soil's pores form a network in which water and gases circulate (e.g. air, which is important for the oxygenation of roots). To survive, most organisms (animals and plants) need air and water. When the soil structure is good, the aggregates are sufficiently spaced to allow macro- and micropores between them and thus facilitate the circulation of air and water (Figure 19).

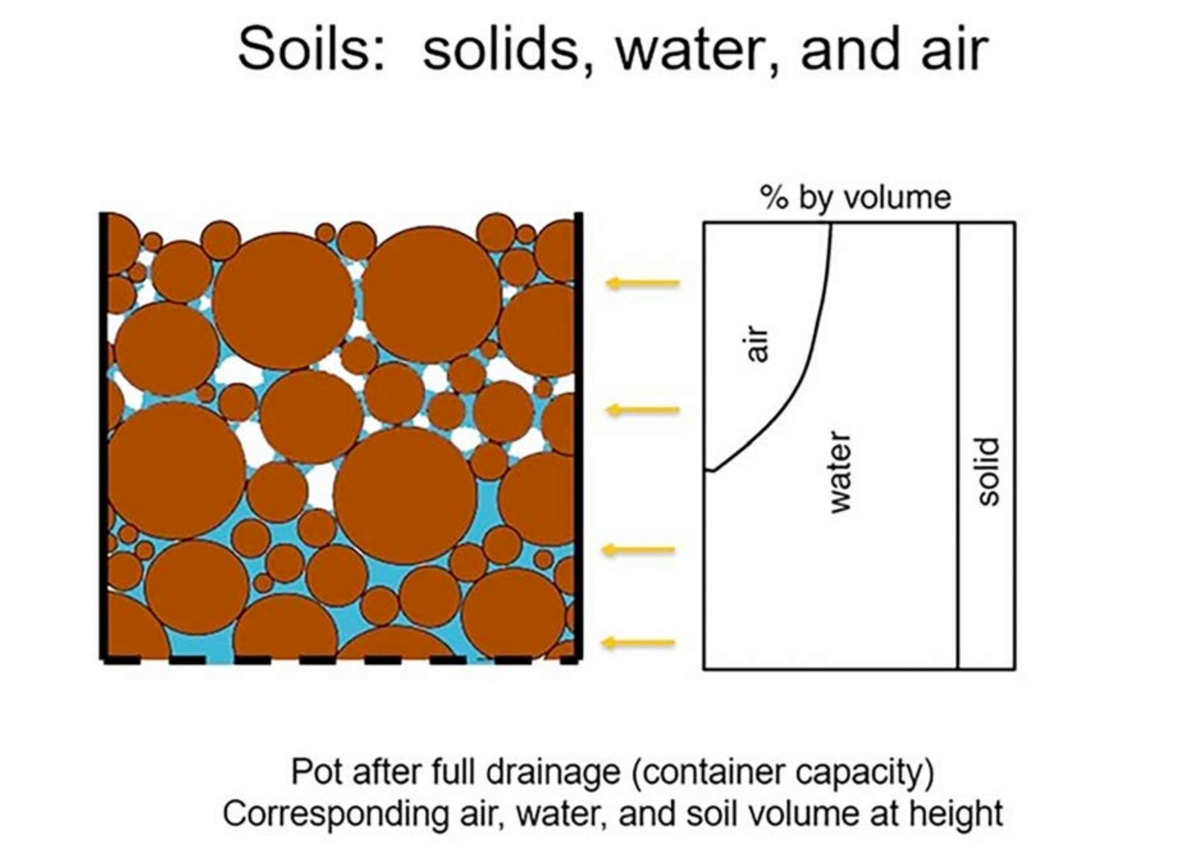


Figure 19 - Circulation of air and water in the soil
Source: UCANR.org

The **pores** of the soil may have different origins.

- The earth's structural elements, aggregates or clods leave voids between them due to biological activity, climate-related desiccation–wetting or freeze–thaw cycles, and agricultural operations. These voids, called **structural pores** or **macropores**, are visible to the naked eye (diameter greater than a few hundred micrometres).
- On a finer scale (from a few dozen micrometres to a few nanometres), other pores make up the principal part of the soil's porosity. These result from assembling particles of sand and silt with clay constituents, and from the arrangement of clay minerals into bands. These textural pores are called **micropores.**

The ability of a soil to allow water to infiltrate or to store it, which affects water availability for plants, depends on the pores' **size** and **spatial organisation**. Large pores promote the rapid circulation of water but do not enable it to be stored. In small pores, water circulates slowly, ensuring that it is stored in the soil.

Types of soil structure

The soil's structure can be described at several scales (mineral particles, aggregates, etc.). There are three main types of structure: fragmentary structure, particle structure and compact structure (see Figures 20 and 21). A fragmentary structure is the one best suited to the majority of crops.

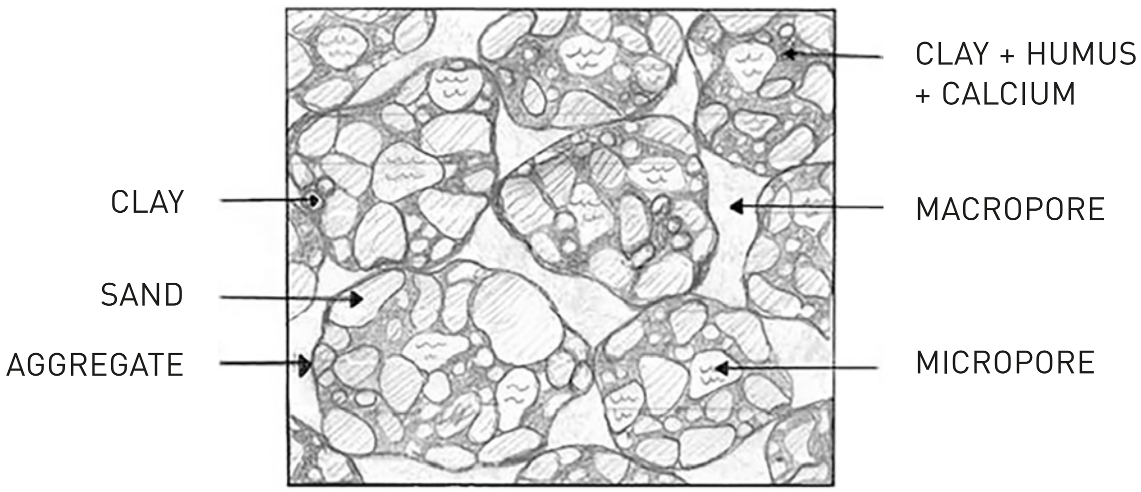


Figure 20 - Soil structure

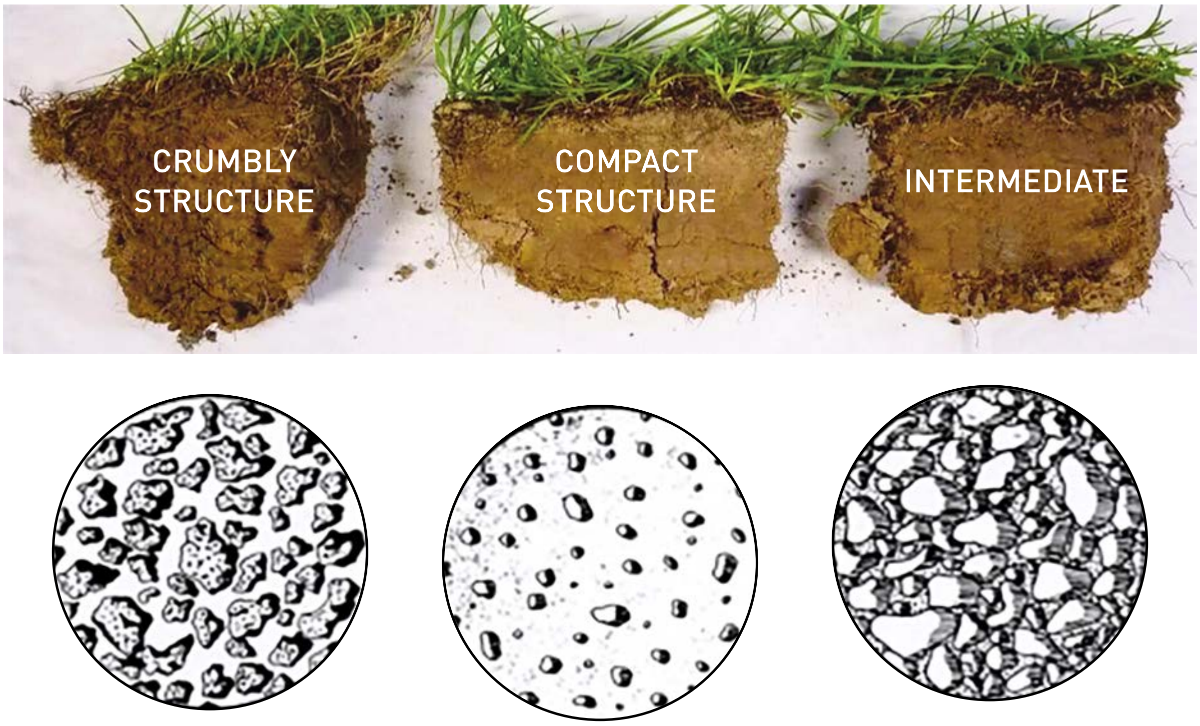


Figure 21 - Observable soil structures :
Source: Supagro, France

A crumbly structure is a sign of good permeability and aeration of the soil. If the soil structure is more solid and more compact, there is a risk of plant roots being asphyxiated and it is difficult for the roots to penetrate deeply into the soil. This may cause deformation of root vegetables or decreased root volume, which reduces plant growth and makes plants more susceptible during periods of drought.

Structural stability of the soil

The stability of aggregates (structural stability) of a soil characterises its resistance to the degrading action of mechanical or physicochemical factors. The soil structure is one of the main factors affecting plant growth due to its influence on root penetration, soil temperature, gas and water exchange, and the emergence of seedlings. It is therefore an important parameter for farmers. Structure is susceptible to changes over time, influenced by both favourable and unfavourable factors.

Favourable factors include:

- organic matter content (taking into account the quality of the humus)
- balanced clay and humus content, rich in humic acids
- presence of exchangeable calcium
- sufficient iron and aluminium oxide content
- presence of earthworms and burrowing species, such as termites, that play a key role in the formation of the clay–humus complex (the soil's biological life).

Unfavourable factors include:

- low organic matter content
- compaction and compression due to the passage of heavy equipment
- mechanical actions of heavy rainfall
- weathering of colloidal cements
- low biological activity in the soil.

1.3.2. Physicochemical properties of soils

1.3.2.1. The clay-humus complex and cation exchange capacity

The clay–humus complex

From a chemical point of view, clay and humus should not normally bind together because the micelles of both clay and humus are (electro)negative and therefore naturally repel each other. However, some communities of soil-dwelling organisms (such as soil fungi and earthworms) are capable of producing such complexes by binding clays and humus.

Formation of the clay–humus complex

Clay (mineral fraction) negative charge −	←	Mineral ions (continuous exchange of ions) positive charge +	→	Humus (organic fraction) negative charge −

The two structures, which are both negatively charged, should repel each other but are closely bound by means of positively charged cationic bridges and biological adhesives. Calcium has a stabilising action: it inserts itself between humus and the layers of clays, forming highly resilient calcium bridges that aerate the soil structure. Magnesium also forms cationic bridges, but with a tightening action of the structure. Bridges made up of ion hydroxides can also be established, but they are less solid than calcium bridges.

Finally, biological activity in the soil plays a fundamental role. The presence of certain organic molecules coats the complexes, which stabilises them in the presence of water. Among these substances is **glomalin**, which is produced abundantly on hyphae and spores of arbuscular mycorrhizal fungi in soil and in roots, or secreted by earthworms. Earthworm droppings (castings) form aggregates from the combination of organic matter (humus) and mineral matter (clay). The formation of a stable clay–humus complex takes place within the digestive tract of the earthworm, which secretes the glomalin, which in turn stabilises the clay–humus complex and makes it resistant to water degradation (Figure 22).

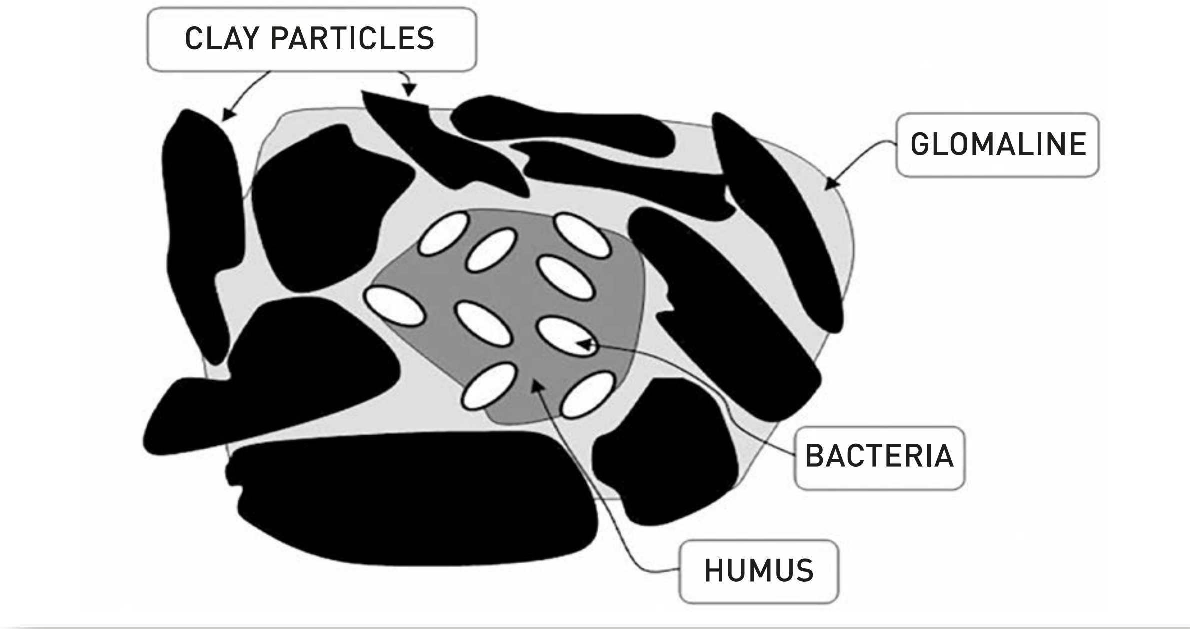


Figure 22 - Role of glomalin in the stability of aggregates

The clay–humus complex is therefore formed from clay and humus minerals. (Humus, which is the stable fraction of the soil's organic matter, has a high tolerance to mineralisation but makes a greater contribution to soil structure.)

The stability of the complexes formed varies according to the following characteristics.

- Clay type: its effect depends on the particle size, the amount of negative charge and ability to bind organic molecules.
- Type of cation binding: this stability depends on the valency and ionic radius of the cation. Monovalent cations generally produce less stable complexes than polyvalent cations.
- Humus type: stability is a variable that depends on the nature of the humic compounds; the more polycondensed these compounds are, the greater the complex's stability.

According to Soltner (2005), when it is stable a clay–humus complex gives the soil properties that are favourable to fertility. The clay–humus complex has the property of retaining the exchangeable cations of the soil solution on its surface (**adsorption power**). These cations can be exchanged with the soil solution and plants, and constitute the soil's chemical fertility reservoir (Figures 23 and 24).

Clay–humus complexes and organic matter

Clay–humus complexes can be found in the soil's constituent aggregates, where they play a major ecological and agronomic role. They are primarily of biogenic origin (created by living organisms), and explain the stability (e.g. rain resistance) and exceptional productivity of soils rich in humus and organic matter. They are very effective in protecting soils that contain them from the sealing effects of heavy rainfall or excessive humidity.

The clay–humus complex has multiple roles:

- the flocculation of colloids, clays and humics promotes an aerated structure and sufficient water storage
- the clay–humus complex linkage inhibits mineralisation of the humified organic matter, and therefore the loss of organic matter likely to bind to the clay
- the clay bound to humus is retained and does not disperse, thus avoiding the clogging and compaction of the soil
- the integration of clay and humus into a single complex increases the soil's capacity to retain bioelements essential to plants
- the absorbent complex plays a fundamental buffering role in maintaining a stable pH in soils.

(Source: Soltner, 2005)

By seeing how the clay–humus complex (CHC) forms and understanding its multiple roles, we can appreciate why the quality and content of the soil's organic matter is also important for soil fertility. Low organic matter levels have an adverse effect on the soil structure (few aggregates formed).

A soil that is rich in organic matter retains water better and is an important source of nutrients for the plant. Nutrients that are readily accessible to the plant are either found in the soil solution or are adsorbed (retained, concentrated on the surface) by well decomposed organic matter or by clay particles. The adsorbed nutrients represent a stock of nutrients readily accessible to the plant.

Figure 23 - Role of the clay–humus complex: when present, it fixes the cations and prevents their loss through transfer (lixiviation) (on the right, the clay–humus complex retains the elements)

Figure 24 - Roots and rootlets, fungal hyphae and 'biological adhesives' stabilise the microaggregates and give the soil a good structure
Source: J.C. de Morales, State University of Ponta Grossa

Cation exchange capacity (CEC)

When a mineral salt dissolves in the soil water, it is found partly in a separated state, split into two ions: a negatively charged anion and a positively charged cation. Since particles of clays and humus are both negatively charged, they retain the cations on their surfaces. Humus has an adsorption power four times greater than that of clays. The CEC therefore corresponds to the **number of negative sites proposed for adsorption** by the soil's humus and clay.

Hydrogen is the cation most energetically retained by the complex. If the soil's acidity is strong, the H^+ ions displace the other cations and occupy the adsorption sites on the clay–humus complex. But when the pH is close to neutral, exchanges can take place between the clay–humus complex surface and the soil solution, and other cations (Ca^{2+}, Mg^{2+}, K^+, Na^+, etc.) can be retained. These are interesting elements as they are essential to the plant's nutrition. Cations that are continually in motion represent the mineral elements in their exchangeable state, which are biologically available to the plant. Chapter 3 provides further information on the nutrients needed for plant growth and production.

What is cation exchange capacity?

Cation exchanges take place between the clay–humus complex and the soil solution, constituting the soil's chemical fertility reservoir; this is the cation exchange capacity (CEC). The soil's CEC, or *T* for total capacity, is the quantity of cations that it can retain on its adsorption complex at a given pH.

The richer the soil is in clay and organic matter (particularly humus), the greater its CEC. The **higher** the CEC, **the fewer cations will be leached** and **the more accessible they will be** to the plants.

The value of the CEC is strongly linked to the C:N ratio and to the soil's pH. An increase in the soil's pH makes it possible to increase the effective CEC, that is, what is available for the storage of exchangeable cations.

The CEC is therefore a good indicator of **soil fertility** (indicating its nutrient retention capacity). Each soil has a very specific CEC that corresponds to the quantity of cations it can fix at a given pH. For a clay soil, CEC is significant: it can release these nutrients gradually to the roots of the plant because it contains very fine particles with a very high relative surface area per gram of soil. By contrast, a sandy soil has a very low nutrient retention capacity. It is not advisable to apply large doses of fertiliser to sandy soils due to the large losses.

The **saturation ratio** (S:T, where S = sum of exchangeable cations and T = total CEC) is the ratio between the sum of exchangeable cations, extracted using a conventional method, and the CEC, most often measured at a standard pH rounded to 7 (Metson CEC).[7] The saturation rate is expressed as a percentage and varies between 50–60% in acid soils to more than 120% in calcareous soils. A soil's exchange capacity is saturated when all H^+ protons or hydrogens are replaced by cations such as Ca^{2+}, Mg^{2+} or K^+, also called exchangeable cations. To neutralise the H^+ ions (OH radicals released by the lime or carbonates contained in the basic mineral), soil improvers need to be added.

Exchangeable calcium

Calcium is the cation predominantly adsorbed on the clay–humus complex. It is naturally present in very large quantities in calcium-rich and calcareous soils. Calcium plays a decisive role in the physical (structural stability, sensitivity to sealing, gas and water exchange), chemical (CEC functioning, desalinisation) and biological (activity of the microbial biomass) state of the soil. Calcium is also a nutrient for plants. But these roles are only performed by certain forms of calcium.

7 The method used in France to determine the potential CEC at pH 7 is the Metson CEC (see Proix *et al.*, 2015).

In nature, calcium can be found in four different forms (Figure 25).

1. **Inactive limestone** (calcium carbonate): this is the coarse state – stone, gravel and sand. The action of carbonic acid from rainwater on these materials is almost non-existent. Another form of inactive limestone is the calcium contained in silicate minerals such as feldspar, micas, amphiboles and pyroxenes.
2. **Active lime**: this is also calcium carbonate, but in a pulverised state. These particles are of a size close to that of silts (20 µm) or clays (2 µm). These particles are readily attacked by carbonic acid from rainwater or by the soil's organic acids. Calcium carbonate is converted into soluble calcium bicarbonate, which will saturate the adsorption complex (clay–humus complex).
3. **Soluble calcium**: this is found or added in the form of bicarbonate $Ca(CO_3H)_2$, lime $Ca(OH)_2$, calcium nitrate $Ca(NO_3)_2$ or monocalcium phosphate $Ca(H_2PO_4)_2$. All of these forms release calcium into the soil solution and help to saturate the adsorption complex.
4. **Exchangeable calcium**: this is represented by the calcium adsorbed on the clay–humus colloids, and more generally on the adsorption complexes. There is generally an equilibrium between the adsorbed Ca^{2+} ions and the free Ca^{2+} ions in the soil solution. Unlike some ions that can be permanently, or even definitively, immobilised on the absorption complexes (e.g. K, NH_4), the calcium ions always remain exchangeable. Calcium solubilised in the soil solution plus the adsorbed calcium (always more abundant) make up the whole of the exchangeable calcium.

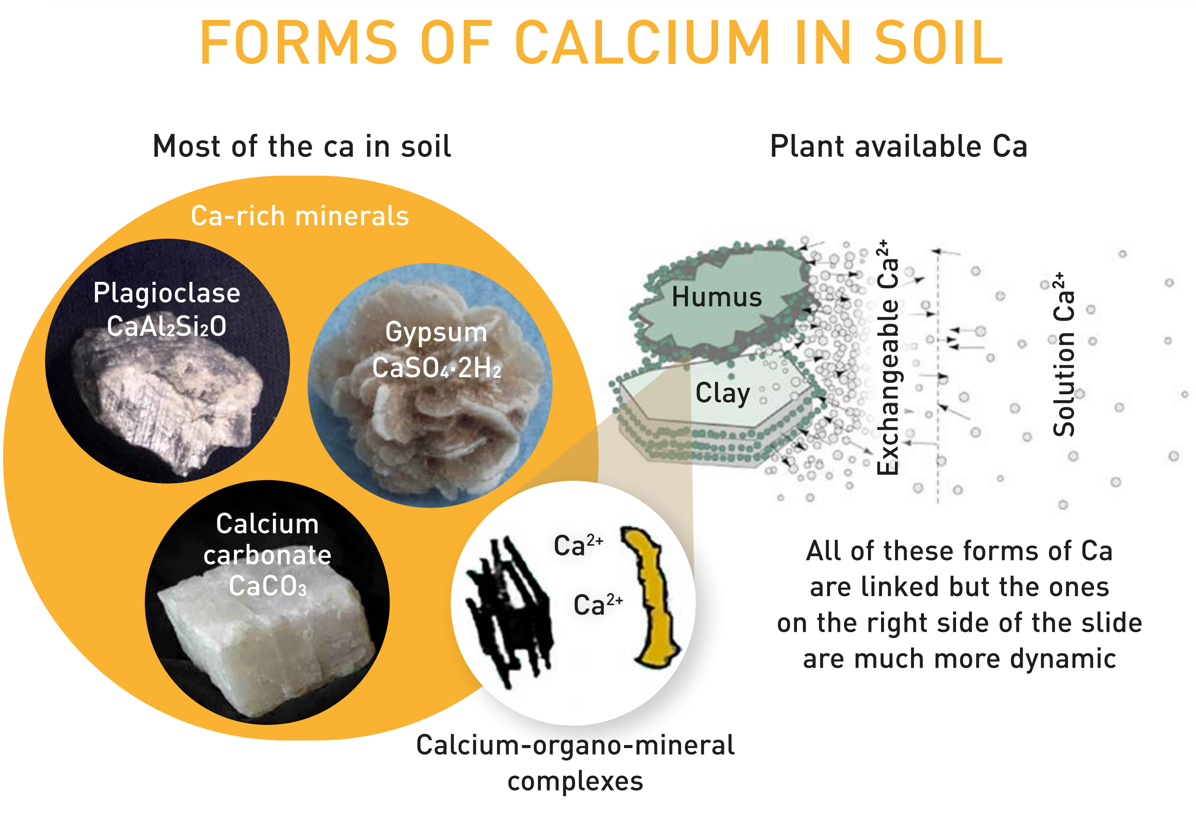


Figure 25 - Forms of calcium in the soil and definition of exchangeable calcium

Another chapter covers the importance of measuring the exchangeable calcium content. Knowing this content, combined with the CEC value, is important for evaluating the proportion of calcium (partial calcium saturation rate of the CEC) and for adapting liming strategies in acid soils or soils with a tendency to acidify.

1.3.2.2. Soil acidity (pH) and soil buffering capacity

Soil acidity (pH)

Acidity is defined by the concentration of H^+ ions in the soil water and is measured by the pH (Figure 26), which determines its degree of acidity or alkalinity (pH_{water}). The (normalised) measurement of pH should be carried out on a volume of soil to volume of solution ratio of 1:5. The pH is a conventional measurement that compares the acidity of soils and shows their evolution towards acidity or alkalinity.

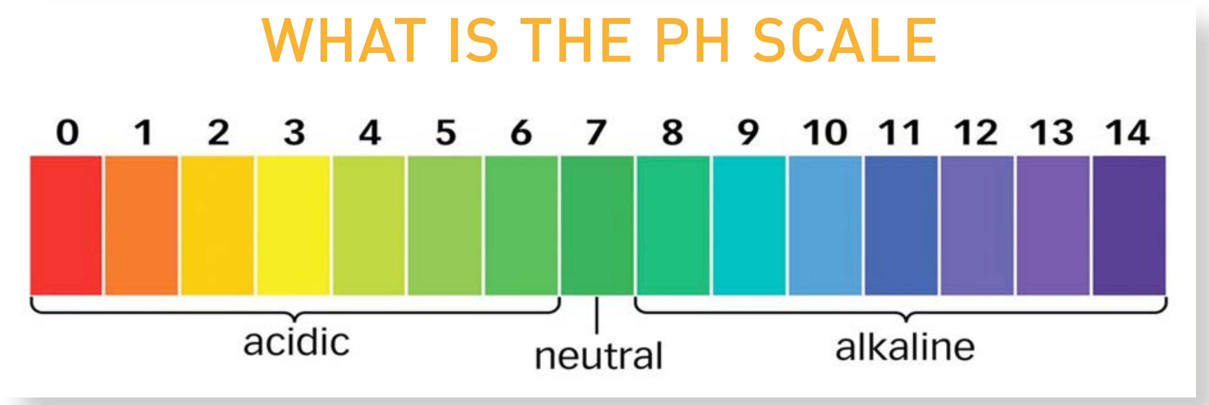


Figure 26 - The pH scale

The vast majority of soil H^+ ions come from the biological activities taking place. A pH_{water} below 7 is typical in an acid soil, while a pH value over 7 is typical of an alkaline soil[8]. Most soils are between 4 and 9, and most plants appreciate a neutral to slightly acidic soil (pH 6.5) (see Table 7).

To encourage plant growth, a soil must not be too acidic or too alkaline. Excessive acidity or alkalinity impairs the plant's absorption of the nutrients contained in the soil. Optimal plant growth is possible on a soil where the pH is between 6 and 7, or in an almost neutral, slightly acidic soil. Note that some plant species have particular growth requirements. An acidic soil may be favourable to the development of plants with higher iron requirements. This is the case for conifers, which grow better in more acidic soils.

8 In non-calcareous soils, the KCl pH can also be measured This is a theoretical pH that establishes the soil's potential acidity. It corresponds to the minimum pH towards which all soils tend due to the acidification process. The KCl pH is always lower than the water pH; the difference between the two varies from 0.2 to 1.5. When the deviation is >1, the reserve acidity is high. When it is <0.5, this reserve is small (see Chapter 3).

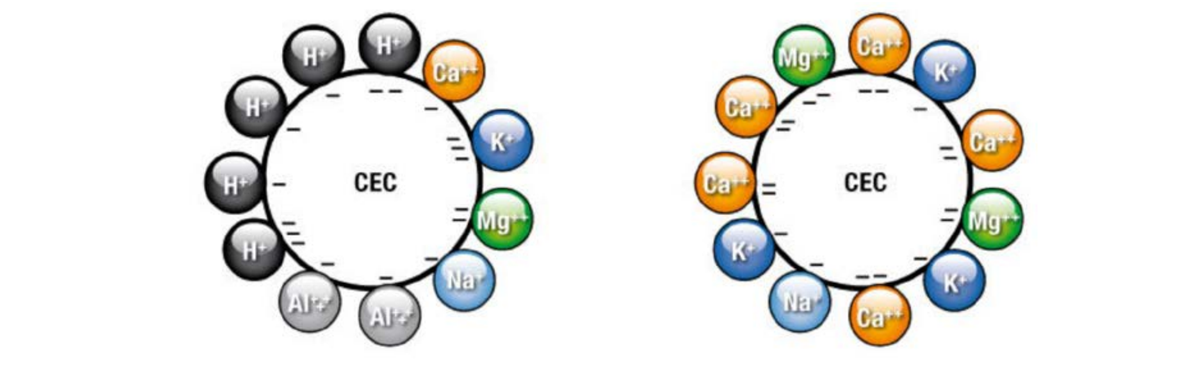
Table 7: pH benchmark values to define the acidic, neutral or alkaline character of soils

Acidic soil	<6.8
Neutral soil	6.8–7.2
Alkaline soil	>7.2

The terms acid and alkaline are also used to describe the rocks or parent material of soils, but in this case do not refer to the material's pH. In geology, these terms refer to the quantity of silica present in relation to that of Mg, Fe and Ca (e.g. granite is an acidic rock while basalt is a so-called alkaline or mafic rock).

The pH varies according to the soil's CO_2, mineral salts and organic matter content. It plays an essential role in the soil's microbiological activity, in the plants' water supply, and in the absorption of nutrients by the roots.

All of the soil's nutrients can be assimilated better in pH values close to neutral (Figure 27). The best example is phosphorus. In acid soils phosphorus forms a complex with iron and becomes insoluble; in alkaline soils it forms a complex with calcium. So there may be phosphorus in the soil, but this phosphorus cannot be retrieved through the roots. It becomes soluble, and therefore able to be assimilated, as soon as the pH is adjusted towards neutral. Adding phosphates to an acid or alkaline soil is therefore a loss, because the phosphates retrograde relatively quickly. The soil's structural stability is also better towards a neutral pH. **It is impossible to manage the chemical fertility of a soil without managing the pH at the same time.**



Acid soil *Neutral soil*

Figure 27 - Comparison between an acidic and a neutral soil
Source: Union des Industries de la Fertilisation, www.unifa.fr

Soil acidification

A soil's natural tendency is **towards acidification.** Mineral cations are replaced by H^+ ions (discussed further in Chapter 4). This can be explained by several parameters, for example the fact that certain soils are more naturally receptive to H^+ ions. This is particularly the case for clay soils, which will be difficult to change. This is referred to as the soil buffering capacity, that is, a strong resistance to pH variations. It is also necessary to mention calcium: if the soil decalcifies, (the causes of which vary), the Ca^{2+} ions make way for H^+ ions and the soil gradually acidifies. Soils also tend to acidify under certain climatic conditions. Fertilisers that contain ammonia, nitrates or phosphates also add acidity.

Acidification of a soil can lead to a degree of **toxicity**. Unlike nutrients, metals are more soluble and therefore more easily assimilated at acid pH values. The most common example is aluminium toxicity. The lower the pH, the more H^+ and Al^{3+} there are on the exchangeable sites, and the greater the toxicity risk. At the same time, there is less Ca^{2+} favourable to a good structure.

Soil buffering capacity

A soil's buffering capacity plays a role in the stabilisation of the soil's pH – its acidity. Depending on their composition and mineral nature, more basic soils may react to changes in pH by neutralising acidity. This chemical reaction is called the buffer effect. For example, a calcareous soil contains a good proportion of calcium carbonate, a basic mineral. It is therefore able to chemically neutralise acids. Variations in pH in this soil type will therefore be less significant than in some others. A soil's buffering capacity (or buffering power) is defined by its ability to withstand pH variations; it is the ability to withstand changes in pH when acid or alkaline compounds are added. The buffering effect results from the balance between substances that release protons (H^+, acids) and substances that capture protons (bases). Soil contains CO_2, mineral salts and organic matter capable of reducing acidification (e.g. due to chemical fertilisers) through neutralisation. Regulation of pH takes place through the clay–humus complex, which is a carrier of negative charges and is therefore a site for cation exchange (H^+, Ca^{2+}, Na^+, K^+, etc.) present in the soil solution.

1.3.3. Biological properties of soils

1.3.3.1. The crucial role of many soil organisms

Several functions depend on biological activity, including the transfer of nutrients from soil to plant; dissolution of minerals from parent rock; mineralisation of organic matter; stabilisation of soil structure through the synthesising of organic substances; cohesion of aggregates; and formation of tunnels to aerate and create porosity.

Biological activity therefore has direct consequences for the physical and chemical properties of soils. The interactions between the soil's (micro)organisms and their trophic relations are complex.

The biological diversity in soil is immense. It is estimated that 25% of land biodiversity is in soils, and only 10% of soil microorganisms are known. Microfauna (size <0.2 mm: protozoa, nematodes, rotifers, tardigrades) and microflora (bacteria, fungi) represent over 3.5 t/ha of biomass. There are 260 million individuals per square metre of soil – an aggregate global mass equivalent to 12 adult cows per hectare (Figure 28).

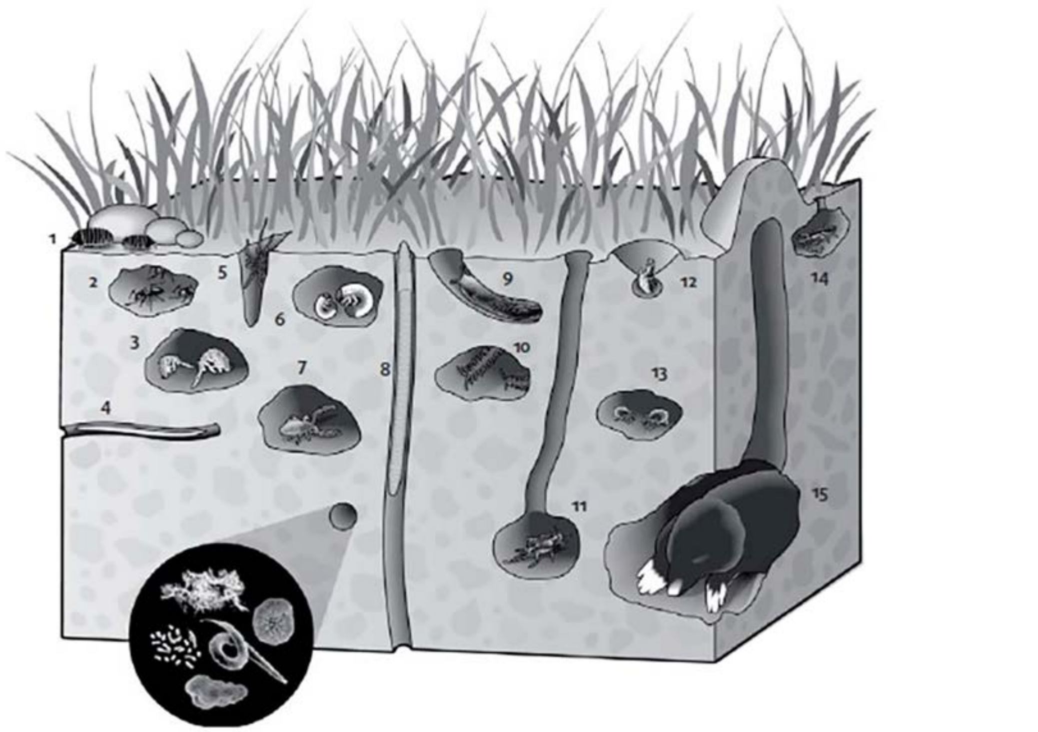


Figure 28 - Life in the soil
Workers in the factory of life under the microscope. 1 Woodlice; 2 ants; 3 collembola; 4 earthworm; 5 spider; 6 beetle larvae; 7 pseudoscorpion; 8 anecic earthworm; 9 slug; 10 myriapods; 11 cricket; 12 antlion larvae; 13 mites; 14 earwig; 15 mole.
Source: Jones *et al.* (2013)

African soils contain an extraordinary range of taxa and species of different sizes, populations and activities. Animals take advantage of the soil in many ways. For them, it is a shelter, a breeding ground, a rubbish dump, a source of food (animal and plant), a dietary supplement (geophagy) and a hygiene facility (dust and mud baths). Depending on how they use the soil, animals can modify its characteristics. Mixing soil particles (bioturbation), decomposition of organic matter and nutrient cycling depend largely on biological activity.

A soil's biology comprises more than 4,000 bacterial genotypes (decomposition, production) and 2,000 species of saprophagous fungi (decomposition, production). It also includes around 1,000 species of invertebrates, including:

- molluscs and insects (early stages of decomposition of litter and conversion of organic matter)
- around 15 species of diplopods – myriapods known as centipedes and millipedes)
- 10 to 12 species of earthworms of various kinds – epigeic worms, living on the soil surface in the litter; anecic, burrowing deep tunnels; soil-dwelling, burrowing horizontal tunnels in the soil)
- 20 to 30 species of enchytraeidae – a family of translucent, tiny white earthworms, sometimes almost invisible)
- 400 to 500 species of mites
- 60 to 80 species of collembola (dissemination of microflora and conversion)
- 90 species of nematodes (regulation of fungi, dissemination of bacteria)
- 60 species of protozoa – amoeba, vorticella.

Biology plays a crucial role in the functioning of soils, and is the foundation for many services performed by the soils (Figure 29). These include:

- recycling of nutrients: fixing and conversion cycles (N, P, K)
- conversion of carbon: essential contribution to humification (storage of carbon)
- maintenance of soil structure: retention of nutrients and water through aggregates formed
- regulation of biological populations, particularly pests (destruction of fungal sclerotia, nematode cysts, insect larvae and pupae, etc.).

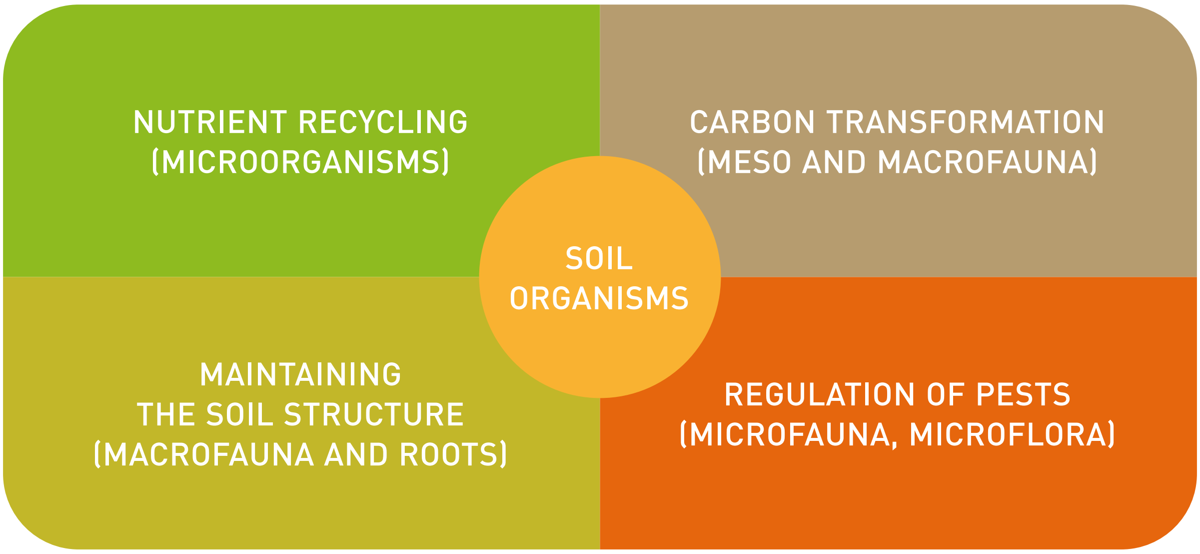


Figure 29 - Importance of soil biology: role of various soil organisms

The different compartments of the living soil have a range of functions, all of which contribute to a healthy soil. Bacteria, for example, are essential regulators of gas equilibria and the soil's biogeochemical cycles. Fungi carry large quantities of water and contribute to the degradation of litter and its conversion into humus.

The fundamental role of the soil fauna lies in converting organic matter and its mechanical action on the soil by forming tunnels, increasing porosity and structuring aggregates. By digging and nesting, animals such as termites, ants, earthworms, moles, rodents, mongooses, birds and large herbivores mix and aerate the layers of the soil. They create passages that facilitate rain infiltration and, through direct digestion and decomposition of litter, they promote the recycling and mineralisation of nutrients. Several species add organic matter from the surface and deposit it deep into the soil. The effects on porosity, aeration, water retention capacity, drainage, bulk density, soil erosion and nutrient content are essential both ecologically and economically. Flourishing populations of invertebrates and microorganisms are considered to be the basis of a healthy soil.

Soil organisms have complex trophic links (Figure 30). These biological interactions provide the soil with self-structuring properties which are expressed at different scales, ranging from microbial films to the macrotunnels of earthworms. Because soil invertebrates are considered a key group in the organisation and functioning of soils, they are referred to as 'engineer organisms'. Their multiple contributions include incorporation of litter into the soil, protection of plants from certain pests, selective activation of microbial activity, and creation of a structure favourable to soil life (incubators for microorganisms). In short, the biological activation of certain groups revitalises the entire system and improve its functioning and primary production. Understanding the soil's biological relationships can be of great practical importance. In rehabilitating soils destroyed by mining, for example, the biggest problem is finding ways to reduce soil compaction. Restoration is doomed to failure if it is confined to revegetation without also seeking ways to repopulate the soil with a range of self-sufficient animals, small and large. In agriculture, the practice of conservation farming techniques requires the presence of a large population of organisms capable of performing bio-ploughing.

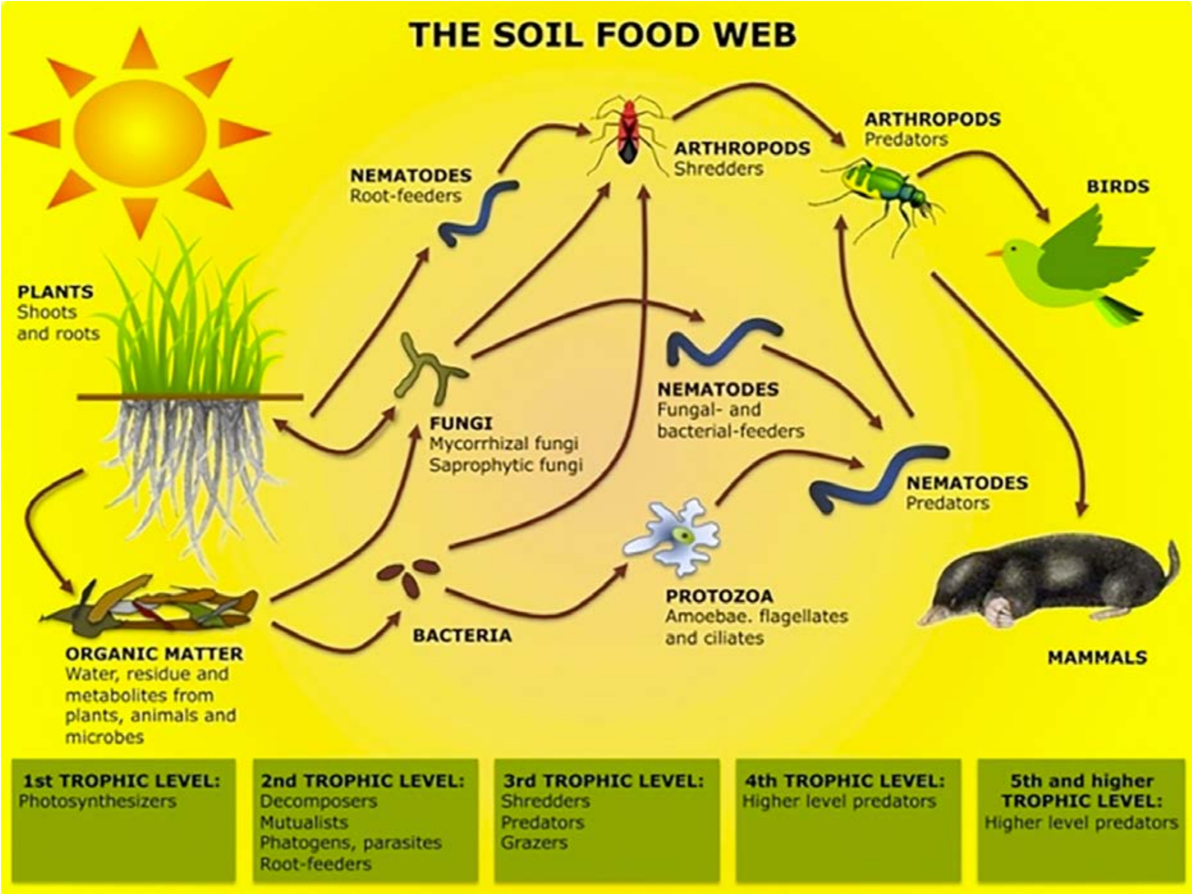


Figure 30 - Complex trophic links between various soil organisms (the base resource is organic matter)

This balance can easily be destroyed by aggressive agricultural work (ploughing, irrigation, excess fertiliser stimulating soil bacteria, accelerating mineralisation, seed or soil treatment, etc.), or by the addition of products that are toxic to microorganisms or soil fauna (pesticides, air pollutants, slurries, manure, etc.). The (micro)fauna of the soil is also very sensitive to weather conditions, and will disappear or migrate towards the lower layers if there is repeated rainfall or strong and repeated exposure to sunlight, making the minerals required for crops with shallow root systems no longer available. Restoring the biological balance of soils is often a slow and delicate process. Although most soil organisms are not visible, protecting them is a priority, as efforts to conserve soil life will help to preserve the plant and animal species that live on the surface.

1.3.3.2. Nitrogen-fixing bacteria in the soil

Among the most important roles of soil biology is the ability of certain bacteria to capture nitrogen. The nitrogen present in soil is in the form of NO_3^- (soil nitrates) and the nitrogen present in air is in the form of N_2 (atmospheric nitrogen). To be absorbed by the plant, nitrogen present in the atmosphere in N_2 form must undergo biological conversion processes carried out by microorganisms called **nitrogen-fixing bacteria**.

These include *Azotobacter* (free bacteria present in the soil, found in large quantities in the rhizosphere, near plant roots) or rhizobia (bacteria found in nodules on the roots of leguminous plants). These nitrogen-fixing bacteria capture nitrogen present in the air as well as in the soil (thus limiting losses in the water table), and return it to the plant in an available form that plants can assimilate (Figure 31).

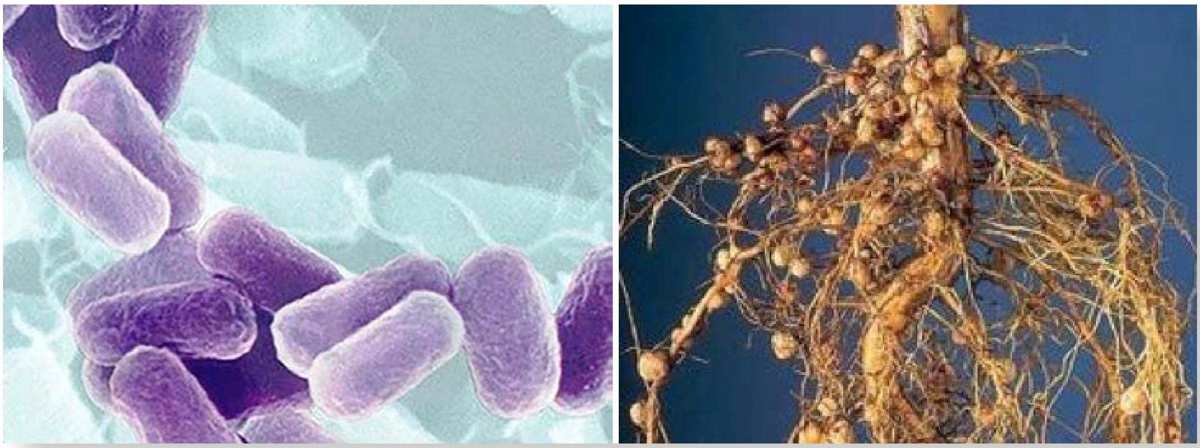


Figure 31 - Azotobacter (left) and Rhizobium (right) nodules on plant roots

Once fixed to the bacteria, the non-assimilable nitrogen is converted and then returned to the soil in the form of NO_3^- or NH_4^+ (ammonium), which can be fully assimilated by plants. Only these nitrate (NO_3^-) and ammonium (NH_4^+) forms can be absorbed by plants at root level. Once absorbed by vegetation, they are converted into organic compounds, mainly proteins, nucleic acid and chlorophyll bases. Since the mineral forms of nitrogen are highly soluble and mobile in soils, some is exported through run-off and percolation towards the hydrological network. The ionic forms of nitrogen are easily soluble and therefore highly mobile. A large quantity of nitrogen is thus transported to water tables and waterways (Figure 32).

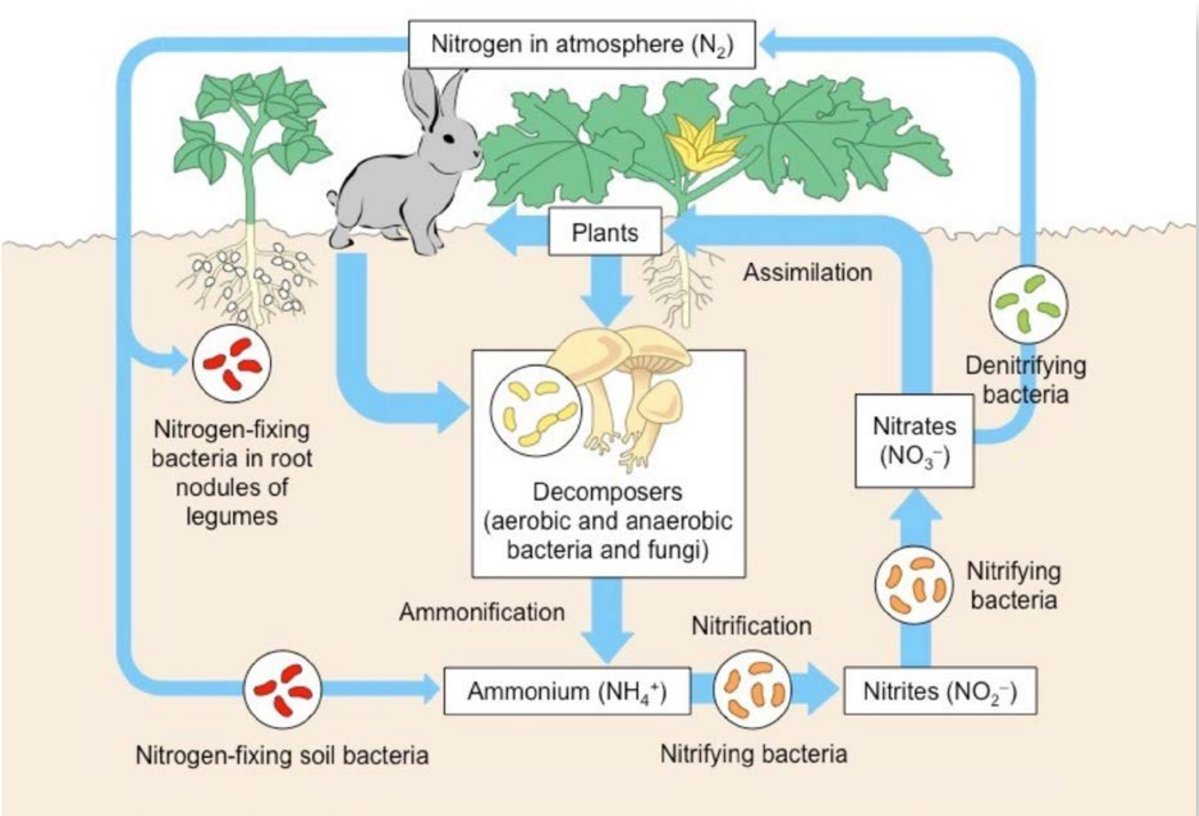


Figure 32 - Microbial processes involved in the nitrogen cycle at soil level
Source: BioNinja

During the **decomposition** of organic matter, inverse chemical processes occur. In anoxic media (with little dissolved oxygen), denitrifying bacteria reduce the nitrates and nitrites in molecular nitrogen (N_2), which is returned to the atmosphere. Through other bacterial processes, nitrate is reduced to nitrite and then in turn to ammonia or nitrogen dioxide.

1.4. THE MAIN FUNCTIONS OF SOIL

Soil is not just a substrate that acts as a medium for plants. Soil contributes to the nutrient cycle, to water and carbon storage, to climate and pest control, and to conserving global biodiversity.

Soil also has many other functions that are beyond the scope of this book. It is a source of raw materials for construction (such as clay bricks or raw clay), for making cooking utensils (such as terracotta pots), for extracting energy and minerals, etc. (see Jones *et al.*, 2013 for more information).

1.4.1. Support for plant production

Soils provide a medium for plants. After capturing CO_2 from the atmosphere for photosynthesis, plants find the water, oxygen and minerals (nutrients) they need to grow in the soil. The soil stores, controls the release of, and ensures the renewal of nutrients and other essential elements. During these biochemical processes, like the water cycle, nutrients can be converted into elements readily available to plants, stored in the soil, or even released into the air or water. These are divided into **macronutrients** (the 20 most important elements, including N, P, K, Ca, Mg, S) and around 15 micronutrients that are necessary but required at very low concentrations).

Plants pick up nutrients in the soil through a process called cation exchange (see Box 6), which depends on soil humidity and light. During photosynthesis, the very fine hairs that cover the plant roots pump hydrogen ions (H^+) from the soil water. These hydrogen ions displace the positively charged ions (namely nutrients) that are retained on the negatively charged particles of soil and organic matter. When these cations are present in the soil solution, the potential energy difference between the soil water and roots moves the nutrients from the most concentrated medium (soil) towards the less concentrated medium (plant).

The soil therefore acts as a sort of pantry of varying sizes, and filled to varying extents. A deficiency in certain elements may cause deficiency symptoms in plants, while at higher levels these same elements may be toxic. Conversely, an abundance of one nutrient may cause a deficiency in another. **Human societies, which feed on plants and animals, are totally dependent on soils.**

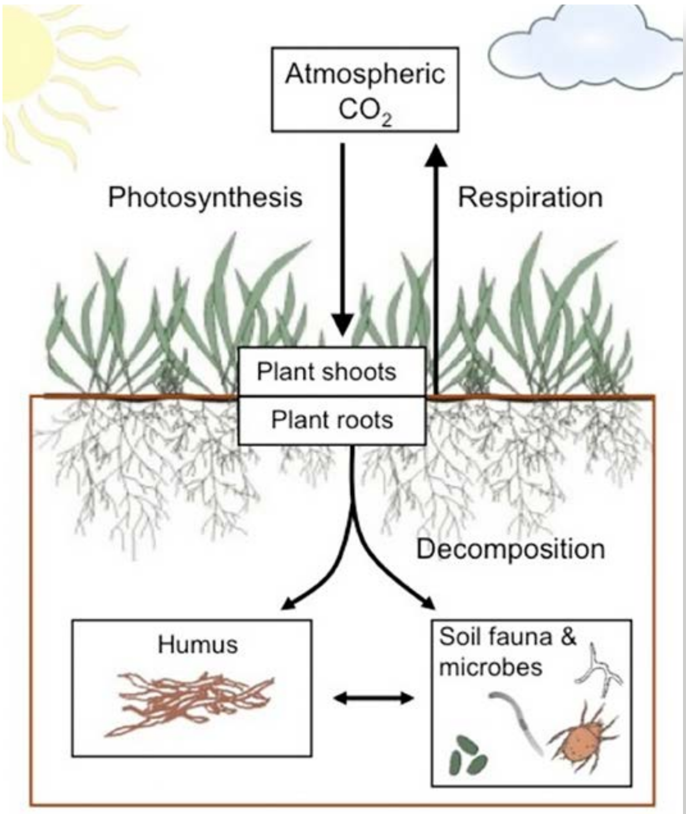
1.4.2. The role of soils as carbon sinks and in the recycling of organic matter

One of the most important functions of soil is its role in the terrestrial carbon (C) cycle by facilitating the conversion of atmospheric carbon dioxide (CO_2) into living matter, and its catabolism and release into the environment. Biology plays an important role in the movement of carbon between the soil and the atmosphere. Soil is **one of the most important carbon sinks in the world** (alongside oceans and forests).

A **carbon sink** is a reservoir that stores atmospheric carbon through a natural or artificial mechanism. The main carbon sinks are the oceans but also the soils (because of the humus they contain), forests in formation, peat bogs, etc. The main mechanism for sequestering atmospheric CO_2 is photosynthesis (specific to photosynthetic bacteria and plants). This metabolic pathway uses solar energy to fix CO_2 as organic matter.

The biosphere now absorbs about 20% of the anthropogenic carbon emitted into the air. Carbon is thus "trapped" in living matter, then more or less permanently sequestered in dead organic matter or in a "biogenic" rock. **The organic biomass present in the soil is therefore a carbon stock.** Indeed, all plant, animal or microbial debris that arrives on the soil decomposes over a period of a few months to a few years on average to transform into humus.

We cannot imagine what the planet would be like without this essential function of waste disposal. In doing so, soils release CO_2, so that they contribute to global climate regulation as both a source and a sink. The nutrients they contained are thus gradually returned to circulation, while stable organic matter (humus) is gradually stored in the soil.



By helping to reduce the amount of atmospheric CO_2, carbon sinks influence global climate and thus all climate-dependent components of the environment.

According to FAO (2002), soil organic carbon is the largest reservoir interacting with the atmosphere and is estimated by between 1,500 and 2,000 Pg C at a depth of 1 m (about 2,456 to 2 m deep). The amount of organic carbon stored in the surface layer of the soil is estimated at 700 Gt (gigatonnes or billions of tonnes) worldwide. Inorganic carbon represents about 750 Pg, but is captured in more stable forms such as carbonates. Vegetation (650 Pg) and atmosphere (750 Pg) store considerably less than soil. Flows between terrestrial carbon or soil organic carbon and the atmosphere are significant and can be positive (sequestration) or negative (CO_2 emission). In Africa, carbon emissions from land clearing and burning are much higher than emissions from the combustion of fossil fuels (e.g. oil and gas). Although savannah fires affect large areas, the CO_2 emissions from combustion are offset by the regrowth of vegetation. Overall, Africa emits slightly more carbon each year than it sequesters.

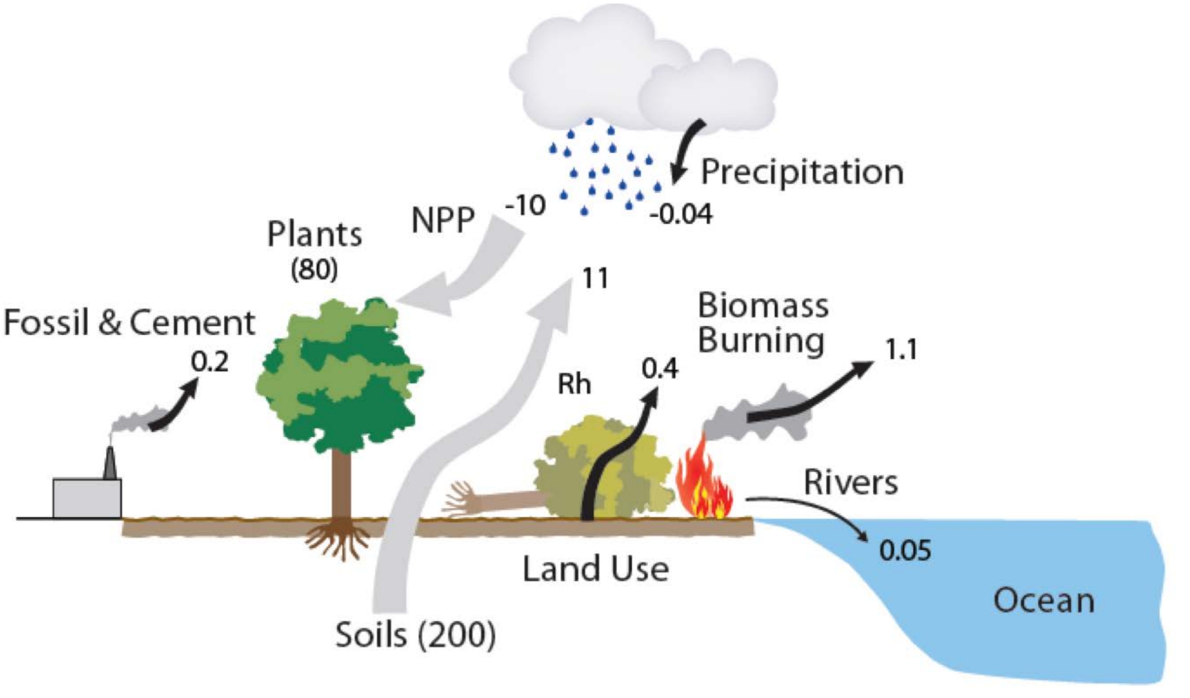


Figure 32 - Carbon cycle in Africa (with PPN = net primary productivity; Rh = microbial respiration) (source: African Soil Atlas)

In Africa (Figure 32), soil is therefore by far the largest reservoir, with about 200 Gt of carbon while vegetation represents about 80 Gt. With 11 Gt of carbon, soils are also the largest carbon emitter in Africa, mainly due to microbial respiration or decomposition of organic matter. However, this quantity is almost compensated by plant productivity (net primary productivity).

Carbon storage depends mainly on the type of soil and its occupation. In the past, the development of agriculture has been the main cause of the increase in CO_2 in the atmosphere, but today the combustion of fossil carbon (6.5 Pg) by industry and transport is the main contribution (FAO, 2002). The lowest stocks are observed under permanent cultivation (34 t/ha) and in some very intensive cultivation areas. Average stocks are found in arable land soils (about 60 t/ha), such as in large intensive cropping plains. Finally, the highest organic carbon stocks (between 80 and 90 t/ha) are found in grassland soils, forests and shrub and/or herbaceous vegetation.

Stocks are low under market gardening, which has intensified significantly. The elimination of tillage increases carbon storage by 0.2 t C/ha/year. Agroforestry makes it possible to significantly increase carbon storage, for example by integrating legumes to ensure nitrogen availability.

Soil organic matter has an important role in the stability of soil structure (anti-erosion effect), the maintenance of plant-friendly microorganisms and invertebrates, and the storage and slow release of nutrients essential to all life forms. The amount of organic matter in the soil is determined by a balance between biological inputs (e.g., plant residues), humus formation rate and humus loss, i.e., vegetation decomposition and humus mineralization. Depending on climate and land use, organic matter can remain stable for long periods of time. However, the level of organic matter in the soil can be modulated by varying the input or loss conditions. Many farming practices, such as crop harvesting or drainage, extract carbon from the soil. No-till or minimal tillage, mulching of plant residues, crop rotation and intercropping of perennials improve the formation and storage of organic matter in soils. It is generally accepted that organic matter contains between 40 and 60% carbon (in % of dry weight).

The organic carbon stock in natural soils has a dynamic balance between the supply of plant debris and the loss due to its decomposition. Under normal soil aerobic conditions, most of the carbon supplied is labile and only a small fraction of what enters the soil accumulates in the stable humic fraction.

Low levels of organic carbon are generally detrimental to soil fertility and water retention capacity, and tend to increase soil vulnerability to compaction, leading to increased surface water runoff and erosion.

Land use changes change average carbon stocks. Moving from a forest to grasslands or crops results in net CO_2 emissions, while afforestation or the return of cultivated land to the grassland leads to net carbon, and therefore CO_2, removals. In equatorial climates, the replacement of forest by crops reduces soil C from 43 to 25 T/ha in 15 years, with inputs decreasing from 11 to 2 t/ha. Cultivation causes the loss of organic matter through oxidation and erosion, leading to the ability to provide nutrients and retain assimilable cations.

1.4.3. Water storage and purification

Water is essential to the survival of almost all living organisms, and soil plays a predominant role in the global hydrological cycle. Most precipitation is intercepted by vegetation or falls directly on the soil surface. Water drips from the leaves or flows along stems and trunks to the soil.

Depending on various factors, such as humidity, texture, organic matter content and soil structure, as well as rainfall, rainwater can:

- soak the soil, where it can be stored to be used by plants
- infiltrate through percolation into the soil, to recharge water tables and aquifers
- flow horizontally or laterally into the soil, and supply rivers, lakes and springs
- be intercepted by roots growing in the soil.

Soil can regulate the drainage, circulation and storage of water and solutes. The soil distributes water for recharging groundwater and feeding plants and soil animals. Sealing the soil can destroy this capacity, causing lethal and destructive flooding. The soil also acts as a filter, protecting the quality of water, air and other resources. Excess nutrients or toxic compounds may be degraded or rendered unavailable to plants and animals (Figure 35) (see Chapter 3; also see COLEACP, 2018).

Plants are only able to use soil water that comes into direct contact with their roots. In general, the distribution of roots is concentrated near the surface. Plants with high root density per volume of soil are able to absorb all the available water. But leguminous plants, which have a low root density, do not capture as much water from the same volume of soil. As a result, leguminous plants are generally more sensitive to water stress than crops with high root density, such as maize.

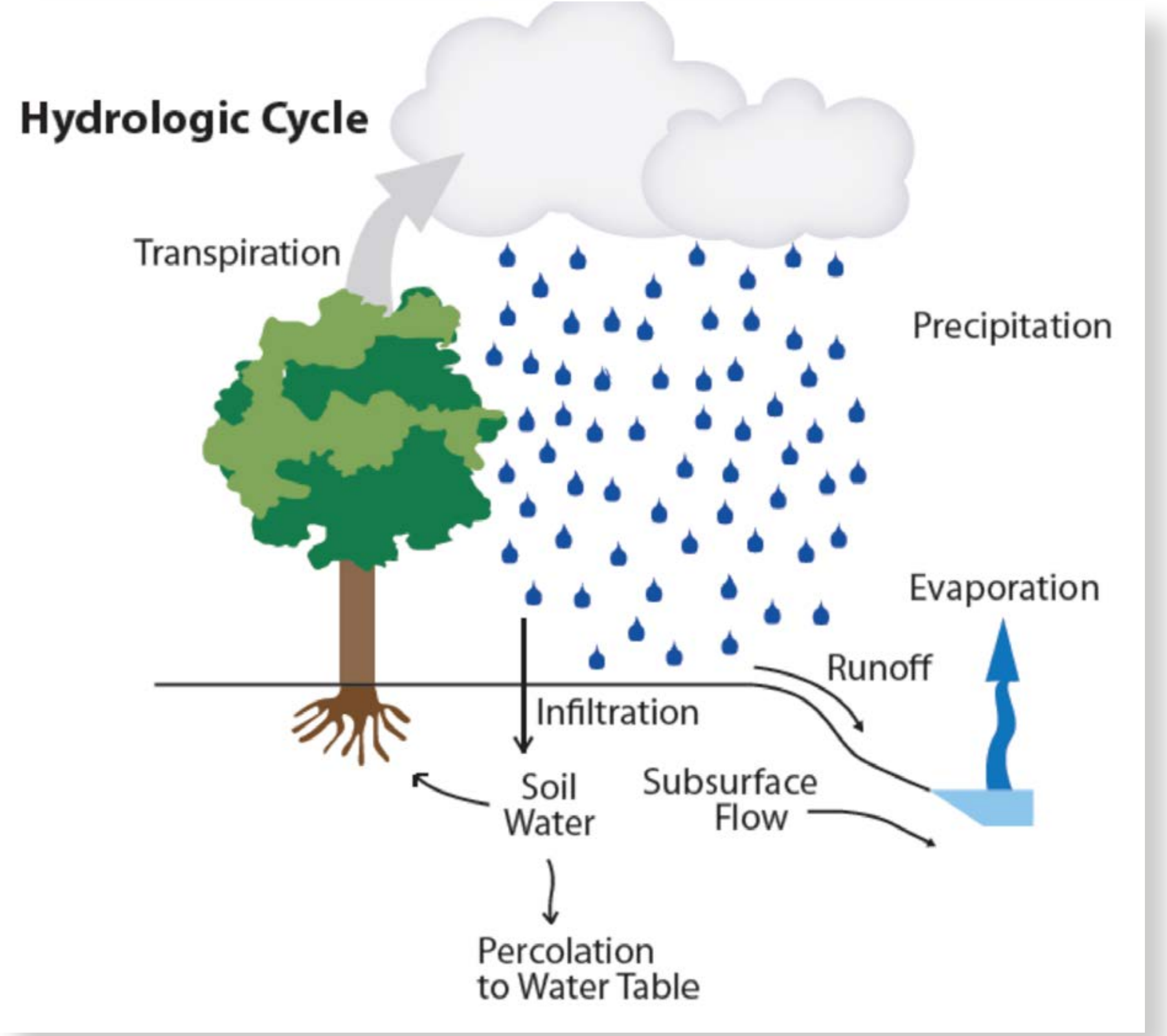


Figure 35 - Hydrological cycle and role of soil in water storage and purification
Source: Jones *et al.* (2013)

1.4.3.1. Storage of water in the soil

Water seeps in and is stored in the soil's pores, which can represent 50% of the soil volume in the first 20 cm. Plant roots pump this water (evapotranspiration), and the Sun's heat causes the water to evaporate. The water rises to the surface through capillarity.

Depending on their size, the soil's pores exert different degrees of water retention, which determine the availability of water to plants (Figure 35).

- **Free water (or gravitational water)** occupies the soil's **macropores**. It can be readily absorbed by plants, but stays in this compartment for only a short time. It leaves the compartment through the action of gravity. This is the phenomenon of soil 'squeezing', which leads to more or less rapid drainage of the water from macropores. The water, replaced by air, is rendered relatively inaccessible to plants. It is not therefore generally included in estimates of soil water reserves.

- **Capillary water** occupies the soil's **micropores**. Capillary water is retained in the soil through capillarity, and the soil reaches a characteristic humidity threshold, called field capacity (see Box). This water is only partially available to plants and will be less available as the size of the pores decreases.
- **Hygroscopic or pellicular water** surrounds the soil's solid particles; it is not available to plants.
- **Combined water** is contained in the soil's solid particles; it is not available to plants.

A soil is said to be saturated when all its pores (micro- and macropores) are filled with water; the conditions are then asphyxiating to plant roots.

An initial part of the water brought by rain or irrigation immediately percolates towards the depths of the soil and is not retained by capillary action; this is **free** or **gravitational water**. The greater this quantity, the coarser the soil texture will be (e.g. sand). A squeezed soil is thus obtained that contains the maximum volume of water it can retain, taking into account its porosity, permeability and particle size, without water being excessive and percolating. This water reserve is called the **field capacity**.

1.4.3.2. Useful water reserve and wilting point

A soil's useful water reserve is the quantity of water the soil can absorb and return to the plant (Table 8). The useful water reserve can also be explained as the difference between humidity at field capacity, and humidity at the permanent wilting point. The useful reserve consists of two-thirds of the readily usable reserve plus one-third of the survival (not readily usable) reserve. Plants begin by using the readily usable reserve, then use the survival reserve (they decrease evapotranspiration activity to survive), but there comes a moment when capillary retention strength exceeds the maximum suction action of the roots (15 bars). This is the **permanent wilting point.** At this point the plant dies because it cannot absorb water from the soil. The wilting point varies depending on the suction capacity of different plant species.

The finer the texture of the soil (clay < silt < sand), the higher the wilting point. The difference between field capacity and the wilting point provides the useful water reserve (UR), according to the following formula:

$$\mathbf{UR = (FCH - HPWP) \times BD \times} Z$$

Where:

FCH = field capacity humidity (%)

HPWP = humidity at the permanent wilting point (%)

BD = bulk density of the soil

Z = rooting depth in (dm)

Table 8: Average values of useful water reserve (UR) according to soil texture

Soil type	UR for 1 m depth (mm)
Sandy	70
Clayey	180
Clay loam	220
Peat	350

1.4.3.3. Water purification

Soil plays a role in water purification. Water is filtered and purified by microbial activity, then transferred through slow vertical and transverse movements towards water tables and waterways. Effective seepage of water into soils prevents run-off and flooding.

Soil is a medium of transit, storage and conversion of many substances, regardless of their inorganic or organic nature, resulting from natural processes or human activities. The constituents of soils, their assemblies and living organisms are the source of several physical, chemical and biological phenomena that determine the chemical composition of water circulating in groundwater and in surface water systems (Calvet, 2003).

1.4.4. Biodiversity reserve

Soil is an amazing factory for sustaining life. Thousands of species (animal and plant) live in the soil. These include many microorganisms, invertebrates and bacteria that make up 80% of the biomass living on Earth. Each species plays its role in converting organic and mineral matter to make it usable by plants – the basis of all terrestrial ecosystems.

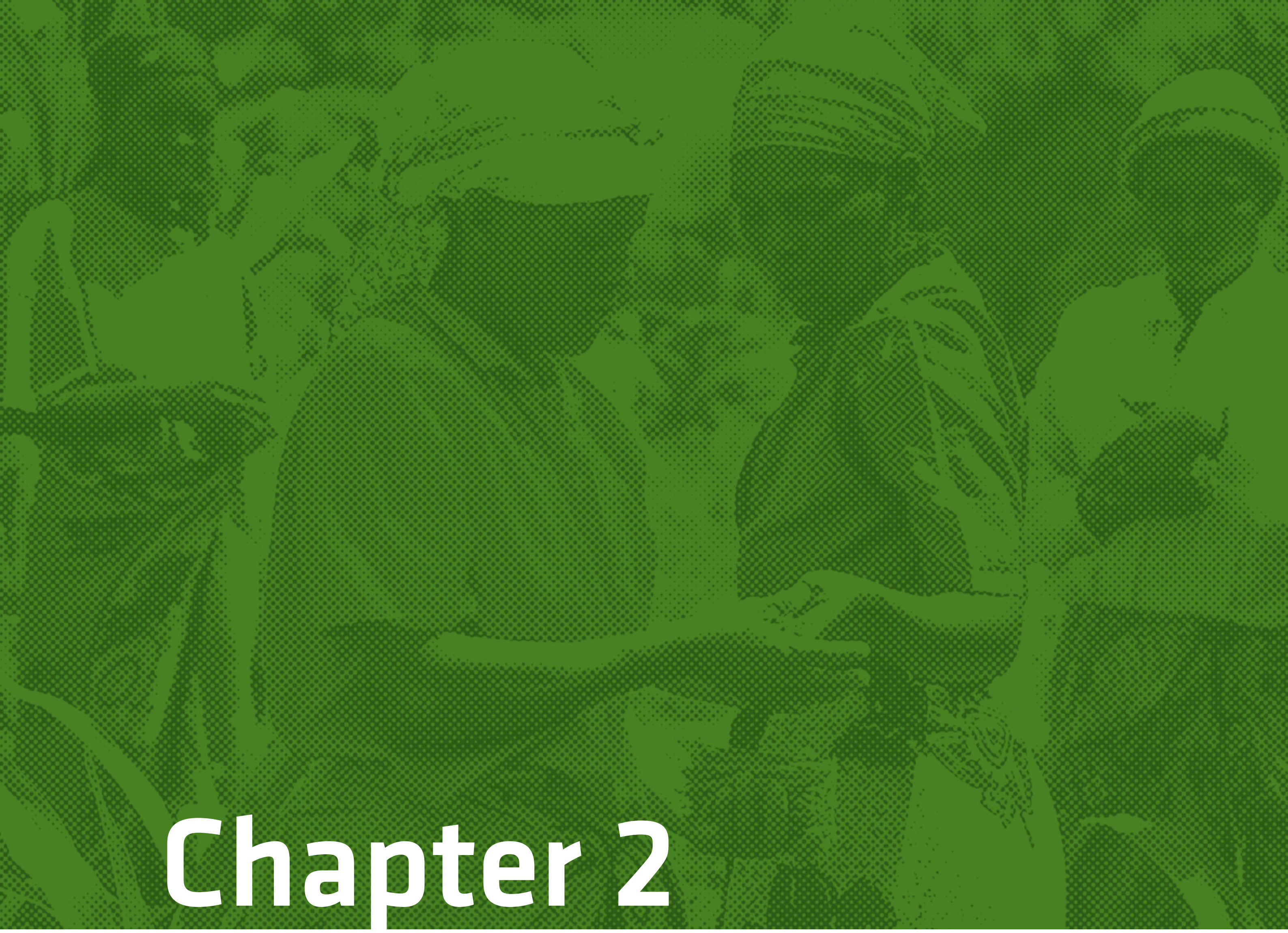
These organisms fulfil multiple functions that promote the structure or maintenance of soil and the growth of plants. Earthworms and termites in particular perform essential actions for building structure and maintaining porosity, stimulating plant growth and defending plants from certain parasites.

According to the Food and Agriculture Organization of the United Nations (FAO, 2017), to promote soil life it is necessary to:

- maintain or enhance the organic matter levels supporting soil biodiversity
- provide sufficient vegetative cover (cover crops, multiple crops, etc.) and nutrient additions
- add various organic soil improvers
- minimise soil disturbance
- avoid salinisation
- maintain or restore vegetation (hedgerows, shelterbelts)

- encourage the use of nitrogen-fixing leguminous species, microbial inoculants, mycorrhizas (spores, hyphae, root fragments), earthworms and other organisms beneficial to the soil
- encourage crop rotation.

The biological fraction plays a crucial role in the functioning of soils and is the foundation for several services performed by soils. This biodiversity in the soil is still little understood because it is complex and has not received a high profile in scientific research. There are over 20 standardised methods for characterising biomass or listing soil organisms. The difficulty is in interpreting the results of counts or measurements of enzymatic activity, for example. When is a soil 'healthy' and in 'good biological health'? When can we say that it 'functions well'? It is very difficult to make a reliable diagnosis. The general recommendation is for long-term, repeated observations at benchmark sites. The usual bio-indicators (e.g. bacterial and fungal biomass, abundance of earthworms, functional diversity of nematodes) are complementary to analyses using new tools (biochemical techniques, DNA analysis, etc.).



Chapter 2

Soil fertility and fertiliser application

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LEARNING OUTCOMES

After reading this chapter, you will:

- understand the concepts of fertility, fertiliser and improver
- be able to define the fertility of a soil, identify the elements that affect soil fertility and know how to manage it sustainably
- know how to assess soil fertility
- understand the role of the key fertiliser nutrients – nitrogen (N), phosphorus (P) and potassium (K) – their forms, sources and risks associated with their loss
- be able to identify the principal soil improvers and the nature and role of each type of improver (calcium, magnesium, humus, organic matter)
- understand the role of the aqueous phase of soil in the absorption of nutrients by plants.

2.1. SOIL FERTILITY

2.1.1. Definition

The **fertility of soil** is defined as being its **capability of supporting the production of crops** (and livestock) (Sebillotte, 1989). In this sense, fertility and productivity are synonymous. A fertile soil is a substrate that can support optimum plant growth, from seed germination to plant maturity.

This support consists primarily of providing:

- an adequate volume of soil for plant root development
- water and air for root development and growth
- chemical elements to respond to the nutritional needs of the plant
- anchorage for the plant structure.

These attributes are often used to describe the overall productive quality of soil used for agriculture.

A view of fertility that is based on the physical components of the environment (soil type, climate, topography, etc.) is too restrictive: soil is not just a combination of organic and mineral elements, but should be seen as a **living organism** that is generated and evolves under the influence of various factors, including (micro) fauna, (micro)flora and, above all, agricultural practices and their use by humans (Samake, 2007).

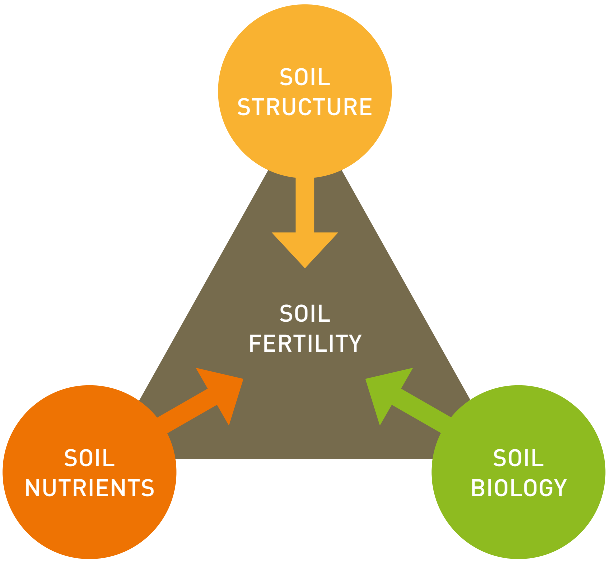


Figure 1- Parameters that influence soil fertility

The fertility of soil depends on its origin (alluvial soils; soils that develop on different types of bedrock), its texture, structure, organic matter content and past fertility management by farmers (adding mineral and organic fertilisers, previous crops, etc.). To explain soil fertility, two types of indicator can be distinguished that evolve over time and are directly affected by agricultural practices.

- **Parameters inherent to soil quality**: these relate to the characteristics of soil in its natural state that allow it to function correctly, such as soil texture, depth and bedrock (mineralogy). While the soil's texture does not normally change over time (as it depends on its composition), its depth may diminish due to erosion, resulting in a change to the texture in the upper layer of the soil. Improving the soil's inherent qualities calls for major resources and is often virtually impossible.
- **Dynamic parameters of soil quality**: these depend on how the soil is managed, and include soil structure, organic matter content, and nutrient- and water retention capacity. Farmers can improve the structure by applying suitable farming practices. Improving organic matter content is a long-term project and can be achieved only after one or two seasons. Increasing the stocks of phosphorus (P) and potassium (K) in the soil over time can be achieved by applying fertiliser and animal manure (the organic matter added provides nutrients and increases capacity to fix nutrients).

As it is very difficult to change the soil's inherent characteristics through normal farming methods, the key objective of sustainable soil management in agriculture is maintaining and improving the dynamic parameters of soil. For example, farmers can manage the soil's organic matter, and therefore the biological properties associated with it, in order to influence the productivity of their land. Regularly adding organic matter can transform a sandy soil to a sandy loam, and a clay soil to clay loam, to obtain the best soils for crops.

Soil fertility management aims to make optimum and sustainable use of nutrient reserves in the soil, mineral fertilisers and organic additions. For most farmers in sub-Saharan Africa, soil fertility management is a key factor in maintaining and increasing their yield and income. How this fertility is managed may not only determine the yield from the current cropping season but may also have a major impact on future yields.

2.1.2. Factors affecting soil fertility

Numerous factors (climate, depth, texture, soil structure, nutrient richness, biological activity), which often interact with each other, affect the soil's fertility, i.e. its capacity to grow crops. Some of these factors (in particular the organic matter content of soil) also have an impact on the sustainability of fertility.

2.1.2.1. Climate

Climatic factors that influence the fertility of soil include **rainfall** (quantity, variations and annual distribution) and **temperature**. The climate provides an excess or shortage (very rarely the optimum level) of energy, carbon dioxide, water and heat that the soil must regulate for good growth and good plant production (Kintche, 2011). Figure 2 shows global climate distribution.

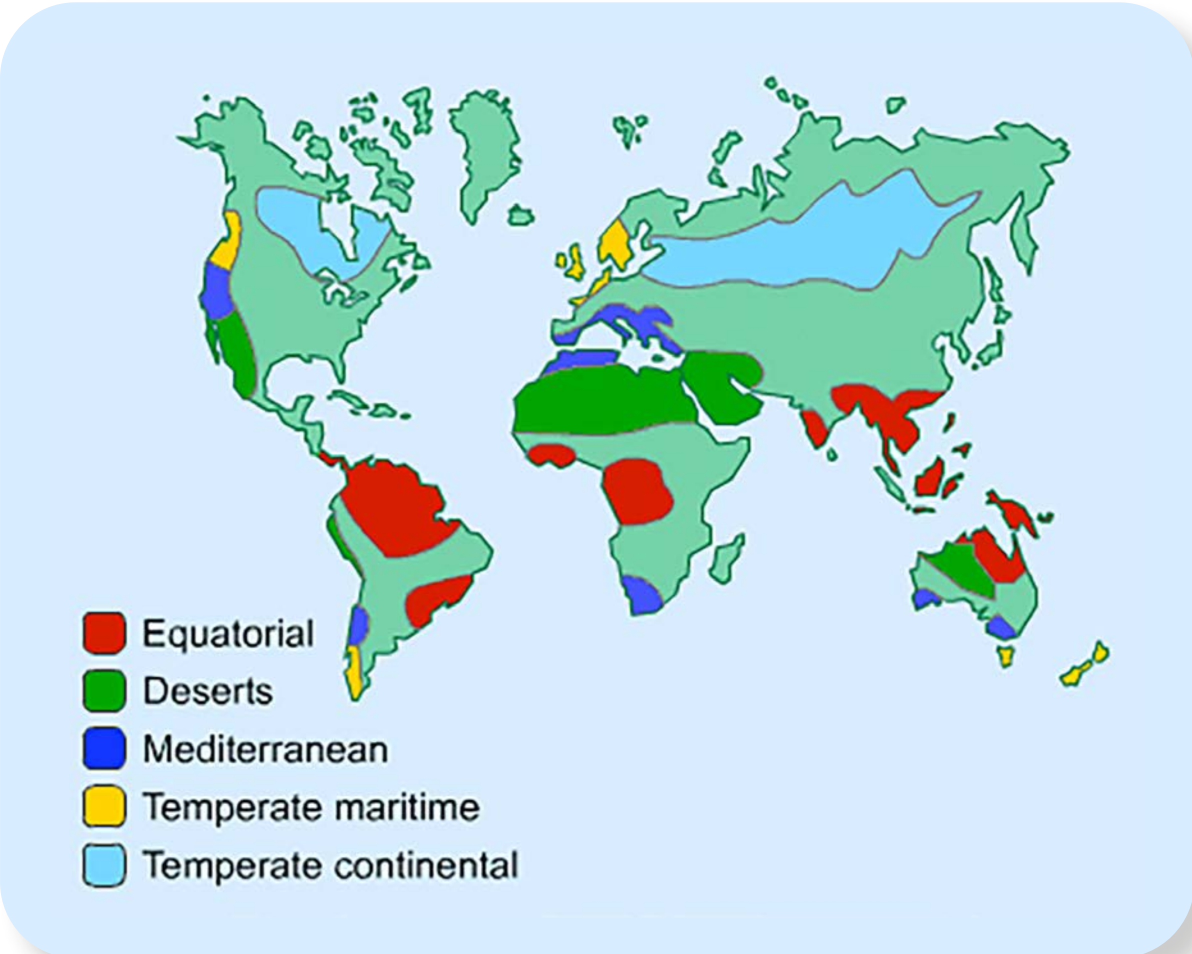


Figure 2 - Map of global climate distribution

The African tropical regions have high temperatures throughout the year and are characterised by their rainfall pattern: two rainy seasons south of the equator and a single and increasingly short rainy season the closer one is to the tropics.

Rainfall patterns have a particular bearing on soil fertility. When the rain is heavy (e.g. during a thunderstorm) and if the land is on a slope, the water runs off down this slope and is lost from the field. The water may also dislodge and mass together surface soil particles (Klaij and Hoogmoed, 1994). Rain then leads to formation on the surface of relatively smooth crusts (soil sealing), resulting in asphyxia and preventing young shoots from emerging. Water cannot penetrate the ground quickly enough, and stagnates on the surface, sometimes for prolonged periods, limiting exchanges with the air. Low rainfall limits the productivity of soils in sub-Saharan Africa. Under drought conditions, although the quality of the soil (structure, fertility, etc.) may be very good, productivity remains very low due to the lack of water (Vallerie, 1968).

2.1.2.2. Soil depth

This is the depth of the soil that can be utilised by deep-rooting crops. Briefly, the greater the depth of the soil, the greater its ability to provide water and nutrients to crop roots, and the greater the agricultural potential. Sufficient depth of soil is a prerequisite for the development of root systems (see Figure 56 and Raoul, 1989).

Figure 3 - Deep soil characterised by the depth that can be utilised by the roots of deep-rooting crops
Source: agriculture-de-conservation.com

The soil horizons accessible to roots, particularly in tropical soils, often have **impenetrable horizons** deep down (ironstone, pan layers, etc.). When these materials are close to the surface, the volume of soil that can be utilised by roots is reduced. This, together with general poor quality, can be very harmful, particularly for plants with taproot systems (Vallerie, 1968). For example, in the Caribbean the productivity of land is limited by insufficient natural fertility and the depth of the soil.

2.1.2.3. Soil texture and structure

Tropical soils often have a coarse texture (e.g. sandy soils), making them act as a filter. Their capacity to retain nutrients is therefore poor (FAO, 1980). There are three types of soil texture (Frisque, 2007).

- **Sandy soils** that cover immense areas in sub-humid or dry tropical regions: such soils provide little water to plants and much of the rainfall is lost through run-off and infiltration. The low clay and silt content means that water is not retained in the soil. The properties of these soils compound the risks of drought associated with a tropical climate. It is difficult for sandy soils to clump, making them light and so it is easy for the roots to gain access, but this also makes them vulnerable to erosion (Raoul, 1989).
- **Silty soils** that seal and asphyxiate: their fine particles leave little space, which leads to the soil compacting under the effect of rain, and water failing to penetrate the soil.
- **Clay soils** that are impermeable: their fine particles act as a glue, preventing water from penetrating.

Soil structure also has a direct impact on fertility. In a well structured soil, sand and loam are clumped into aggregates (small clumps) by clay, humus and calcium (Soltner, 1977). These aggregates improve the soil's resistance to erosion, prevent the phenomenon of surface sealing, encourage the circulation of air and water, and consequently make good root development possible and foster good biological activity in the soil.

Soil **porosity** provides space for roots and microorganisms to breathe, and for storing water. Well drained soil provides sufficient humidity for plant growth and sufficient aeration for roots to function well. Large empty spaces between aggregates (macropores) allow water and air to circulate and roots to sink into the soil. Small empty spaces (micropores) hold the water the plants need.

In very dry soil, all the pores (small holes and channels between soil particles) are filled with air, and the functioning of the root system and plant growth are compromised due to dryness. In flooded soil, the pores are saturated with water, preventing the roots of most crops from breathing. The crops may therefore die. The only exception is rice, which has roots that can breathe in stagnant water.

This ideal structure is referred to as a crumbly soil structure (see section 1.3). Biological activity is fostered and the efficacy of mineral and organic fertilisers is enhanced. Roots can explore a vast area and thus have access to a greater surface area that is in contact with the soil. Crops therefore have access to a **large mineral reserve** and **greater supply of water** for nourishment (Breune *et al.*, 2000).

Structure therefore plays a crucial role in natural soil fertility. However, it is difficult to characterize soil structure precisely with simple terms and to identify the exact type of structure easily. The structure of soil is sensitive to the action of atmospheric agents, and particularly to the action of water. **Structural stability** defines the resistance of soil aggregates to the action of various factors, among which water plays an essential role, directly or indirectly (Vallerie, 1968).

2.1.3. Importance of organic matter for soil fertility

To maintain soil fertility, the organic matter contained in the soil must be preserved. The role of humus in plant nutrition has been underestimated in the past, and the critical multifunctional roles played by organic matter and soil biology in providing the requisite quantities of minerals have been overlooked. The presence of fresh organic matter and humus in the soil is essential to maintain the wide range of nutrients required by plants. Humus gives the soil a dark colour and makes it possible to retain large quantities of water and nutrients. This can be achieved through appropriate farming practices and using manure, compost or other organic materials, depending on what is available.

If the soil is highly degraded, the use of **chemical fertilisers** may be necessary. Chemical fertilisers make it possible to restore fertility to the soil very rapidly (but also temporarily), as the plant can use them as soon as they dissolve in the soil. In contrast, organic matter requires some time before it can be converted into humus and liberate nutrients.

Despite its crucial role in preserving soil fertility, the required quantity of organic matter (manure, straw, etc.) is simply not available for the majority of small-scale farmers. In the case of **manure**, for example, there are often insufficient animals to produce it, particularly when drought results in a decrease in cattle numbers due to lack of fodder. Farmers can only increase their number of cattle if they have sufficient pasture land or if they are able to provide enough fodder – which in turn requires increased crop productivity. Analysis of farming systems shows that there is competition for straw for uses other than making compost. Where straw is used as a cattle feed, there is not enough for preparing compost.

It is possible to produce **organic inputs** by planting **cover crops** such as *Mucuna pruriens* (velvet bean) and other plants that serve as green manure, and are used as both nutrient inputs and soil improvers. However, even when promising results have been obtained by researchers in controlled farm trials, farmers rarely adopt such practices as they require highly intensive manpower, cannot provide sufficient nutrients to sustain productivity and do not produce products that can be consumed or sold to the market.

2.1.4. Importance of soil biology for soil fertility

Most conventional farming systems have ignored the key multifunctional roles of **soil biology** and its relationship with the productivity of agricultural land. However, soil organisms also play a role in both the physical and chemical quality of soils.

Macroorganisms (earthworms, termites, beetles, small rodents, etc.) dig large pores or burrows to great depths, facilitating drainage and aeration, and contributing to soil maintenance, ploughing in litter and the decomposition of crusts, moving soil particles, and the formation of pores.

But it is **microorganisms** that have the greatest impact on soil fertility, in the following ways.

- Microorganisms make nutrients available by assisting in the decomposition of organic matter and releasing nutrients, contributing to the dissolving of minerals in rocks and ensuring the chelation[9] and complexing of nutrients.
- They improve soil structure through the formation of aggregates obtained during decomposition by mixing clay with other particles in ad hoc open forms that are then stuck together with humus, organic polymers and fungal hyphae (Figure 57).

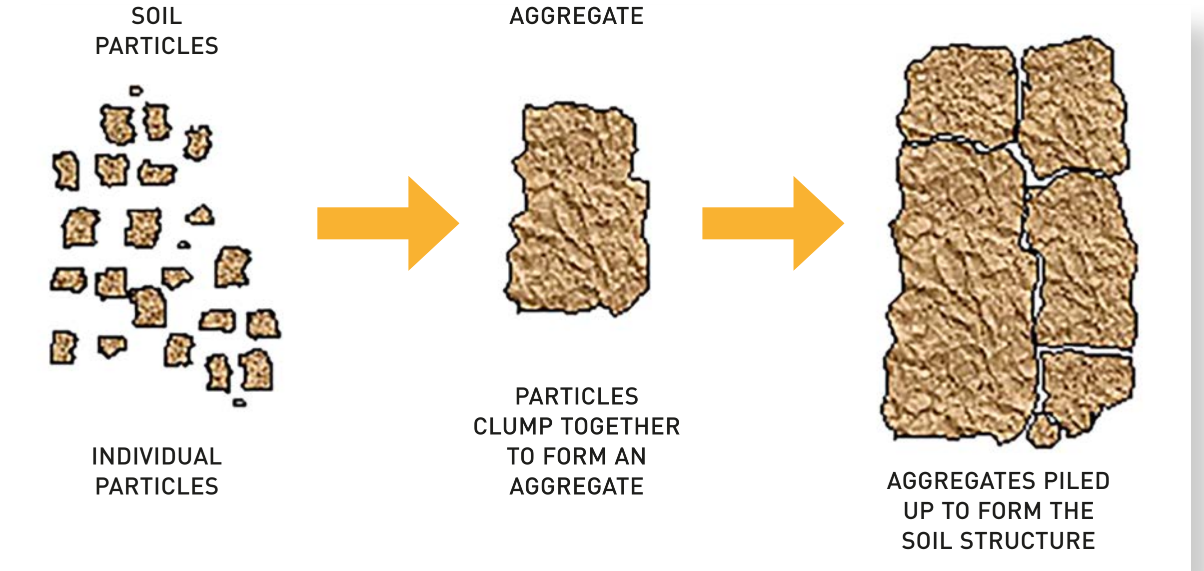


Figure 3 - The formation of aggregates

- They capture and fix nitrogen: numerous studies show that microorganisms produce a range of components that plants use for nutrition. The most commonly known microorganisms are *Rhizobium* bacteria that live in the nodules of legumes. They capture nitrogen and convert it into forms that plants can use. Microbial inoculums have now been produced to form coatings that protect young plants.

9 Chelation is a physico-chemical process during which a complex (chelate) is formed between a ligand (the chelator) and a metal ion (cation), which is therefore complexed (that is to say, chelated) by at least two coordination links (which differentiates "chelate" from "complexes", which are comparatively less stable in the soil). Organic acids present in decomposing organic matter can form chelates and link a variety of metal ions in the soil, such as iron, copper, zinc and aluminium. In addition to microorganisms, most plants secrete chelates through their roots to facilitate the absorption of certain soil elements.

- They increase the absorption of nutrients: groups of microorganisms that are beneficial to soil fertility are **mycorrhiza** and related **fungi**. These fungi live in the roots of plants (the **rhizosphere**) and extend their mycelium filaments into the soil to take up minerals, exchanging these minerals for glucose. They play an important role in the absorption of phosphorus by numerous plant species: they have enzymes that can extract phosphorus from rocks, trap it in molecules as iron phosphides and tricalcium diphosphates, and release it in plant roots.

The greatest concentration of microorganisms in the soil is found in a narrow area close to plant roots – the rhizosphere. The concept was first proposed in 1904 by the German scientist Hiltner, who noted that microorganisms fed from the sheaths produced by roots as they grew, along with several other exudates such as sugars and amino acids (Figure 4).

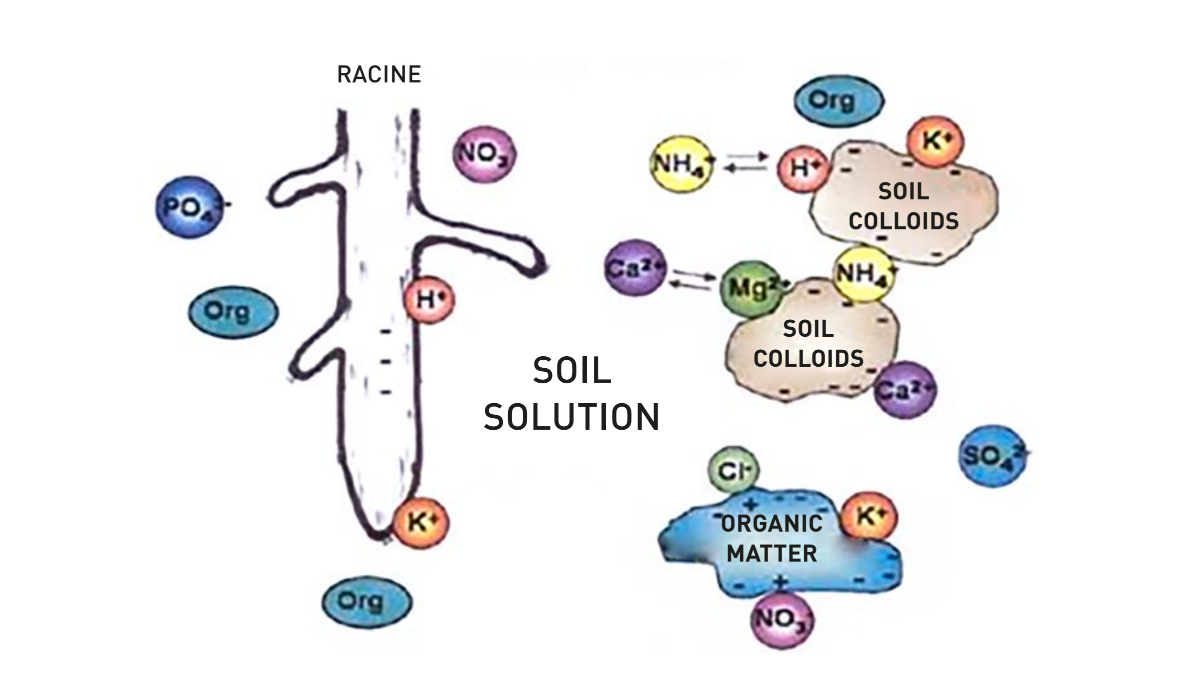


Figure 4 - The soil rhizosphere system

Hiltner was convinced that root exudates from different plants promoted the development of different bacterial communities. Its definition of the "rhizosphere" in 1904 focused on the idea that plant nutrition is considerably influenced by the microbial composition of the rhizosphere. Hiltner observed bacterial cells even within the rhizoderm of healthy roots. In analogy with fungal root symbionts, Hiltner called the bacterial community closely associated with roots "bacteriorhiza". In its rhizosphere concept, Hiltner also considered that beneficial bacteria are not only attracted by root exudates, but that there are also "uninvited hosts" that adapt to specific root exudates. He put forward the theory that plants' resistance to pathogens depended on the composition of the rhizosphere microflora, and suggested that the quality of plant products could depend on the composition of the root microflora.

Science relating to the rhizosphere has made huge advances, although the complexity of interactions within the broad biodiversity surrounding roots in soils means that they are not yet fully understood, and consequently the results are not yet in widespread use in agriculture.

Soil biology therefore plays numerous roles in optimising agricultural production, and all sustainable fertility management must avoid jeopardising the **life and balance of the soil**, whether as a result of disruptive farming practices or the application of chemical (or even organic) products that are toxic to such microorganisms.

2.2. ASSESSING SOIL FERTILITY

2.2.1. The main criteria used to assess soil fertility

The main criteria used to assess soil fertility are summarised in Table 1.

Table 1: Criteria for assessing soil fertility

Soil property	Characteristics of a fertile soil
Depth	Deep soil provides good space for roots and a large reserve of nutrients and water for the soil. Deep roots are also protected from drying out during droughts (Boeuf, 1929).
Texture and structure	Medium-sized grains and a good structure promote the development of a good root system, good infiltration, conservation of water and good aeration (Morellet, 1998).
Soil reaction	A pH close to neutral (pH 6–7) helps plants to assimilate nutrients. For example, in alkaline soils phosphorus combines with calcium, whereas in acid soils it combines with iron and becomes insoluble. In both cases, it is not available to plants. In a pH-neutral soil, it is soluble and can be assimilated. The nature and intensity of biological activity in soil is influenced by the pH (Pousset, 2002).
Mineralogical composition of the parent substrate (bedrock) *Changes to the bedrock lead to the formation of soils and release of nutrients. The initial mineral content of bedrock and the nature and intensity of the alteration process determines the nature and quantity of nutrients released.*	A heterogeneous substrate (sand-clay-limestone, etc.) gives a soil that is rich in a variety of nutrients and nutrition that is more or less balanced (Duval and Alex, 2011). In contrast, a homogeneous parent substrate results in a soil that is lacking in nutrients and has a nutritional imbalance.

Nutrient content	A reserve content of major nutrients (nitrogen, phosphorus, potassium) and trace elements (boron, chlorine, copper, iron, manganese, molybdenum and zinc) and an optimal content of the mobile fraction encourages optimum and sustained plant growth (Naitormbaide, 2007).
Humus content and composition	Colloids improve soil structure, forming easily mobilisable complexes with mineral substances and activating the life of the microorganisms for which they act as a medium and food (Soltner, 1977).
Toxic products (to soils, plants, and also humans if accumulated in the harvested crop) *Certain agricultural practices cause heavy metals to be incorporated into the soil (application of fertilisers, liquid manures, manures, composts and sewage sludge).*	Metal trace elements (lead, cadmium, copper, and less commonly zinc and mercury) are present in the soil at (very) low concentrations. When they are taken up by plants, they may make the products harvested unfit for human consumption. Concentration limits exist for lead and cadmium in particular.

2.2.2. Determining soil fertility

In chapter 1, simple tests are presented for assessing soil texture and soil structure. Producing a soil profile is of great benefit for assessing the soil's depth and ascertaining the rooting zone. Methods to determine the soil fertility of a given area include visual diagnosis, indicator plants, analysis of plant tissue, soil analysis, and diagnosis of soil structure and biological activity.

2.2.2.1. Visual diagnosis

Soil colour is a good indicator of its organic matter content and nature (soil classification). From the earliest soil studies, the need was recognised to codify visual assessments of soil colour based on comparisons with coloured samples (Munsell system, code or chart).[10]

By the 1950s, soil scientists had achieved a range of sample colours aligned with those most frequently observed. Soil colour is generally compared on the ground, in daylight, against the colours of bordering beds. By moving the soil sample in the intended windows under each coloured sample, it is possible to identify the one with the closest colour match, and its characteristics can be noted (colour, clarity, purity).

The Munsell chart is used to determine organic content. A light soil colour is negatively correlated with the level of carbon: the more carbon there is, the darker the colour. The accuracy of this colour determination method depends largely on the degree of care taken. Furthermore, a large number of permanent (texture, calcium, iron, etc.) and cyclical (humidity, roughness) features may affect soil colour.

10 Munsell Soil Color Charts, https://munsell.com/color-products/color-communications-products/environmental-color-communication/munsell-soil-color-charts/

2.2.2.2. Indicator plants

Farmers also estimate fertility based on a long-established knowledge of the indicator value of vegetation or certain observable signs on the soil surface.

In agriculture, indicator plants have long been used to identify what is known as the natural environment, its fertility in general, its particular cultural aptitudes or, more precisely, certain soil and climate constraints or conditions. Indeed, if the floristic composition of spontaneous vegetation is the result of a precise combination of ecological factors, the presence of a species has an informative value (e. g. plants indicating acidic soils, calcareous or sandy soils, fertile soils, heavy soils, compacted soils, saline soils, etc.).

It is this informative value of vegetation and certain edaphic signs that allows farmers to decide whether or not to place a crop in a plot (today guides are available in Europe such as Gérard Ducerf's Guide, PromoNature, in three volumes). According to M'Biandoum et al (2002), it appears that the fertility level of a soil can be assessed by identifying two groups of weeds: "guide herbs", which are non-discriminatory but whose importance guides the diagnosis, and "bioindicating herbs" whose presence or absence is discriminatory. The presence or absence of these species allows the farmer to determine whether the plots are fertile or degraded. From there, he decides whether or not to exploit the field. The plant species that grow on the plots are used to make several decisions: (1) that of deciding to cultivate a plot; (2) that of deciding on the modalities of this cultivation; (3) that of deciding to abandon this field in order to put it into set-aside.

A few examples of bioindicator plants (in Cameroon) can be grouped in a table (adapted from M'Biandoum et al. 2002):

Degraded soil indicator plants	Fertile soil indicator plants
Ageratum lonyzoïdes	*Andropogon gayanus*
Amaranthus graecizans	*Andropogon tectorum*
Amaranthus spinosus	*Cassia mimosoïdes*
Brachiaria lata	*Celosia argentea*
Bulbostylis barbata	*Chloris pilosa*
Celosia argentea	*Crotalaria retusa*
Chrysanthellum americanus	*Digitaria argillacea*
Commelina benghalensis	*Hyptis suaveolens*
Commelina forskalaei	*Indigofera hirsuta*
Cucumis melo	*Ipomoea dichroa*
Cyperus amabilis	*Kyllinga tenuifolia*
Eleusine indica	*Pennisetum pedicellatum*
Indigofera dendroïdes	*Phyllanthus amarus*
Indigofera hirsuta	*Physalis micrantha*
Portulaca oleracen	*Rottboellia cochinchinensis*
Striga hermonthica	*Triumfetta pentandra*
Tephrosia bracteolata	
Tribulus terrestris	
Waltheria indica	

However, according to these authors, caution should be exercised in the interpretation. The floral richness of a terroir depends on the climate of the region, the type and richness of the soils. In Cameroon, in two different contexts, the same plant will not necessarily have the same meaning. Thus, for example, while in Mafa Kilda Commelina bengalensis is considered by farmers as an indicator of fertile soil. However, in Fignolé this species is considered as an indicator of degraded soil. In fact, in Fignolé, the climate is wetter than in Mafa Kilda, biodiversity is higher, the soils are still very rich and above all the space is available, which allows long fallows and a very demanding choice of the best plots. In Mafa Kilda, the space is saturated, and farmers cannot be so demanding. Thus, land that is considered fertile at Mafa Kilda would be fallowed at Fignolé, because it is already relatively poor, and farmers then prefer to clear it again, since the available space allows it.

The richness of the soil allows the establishment of a very specific flora. Thus, if the phosphorus in the soil is blocked, some weeds see their dormancy rise and germinate (sometimes seeds about a hundred years old can germinate). Some farmers make the link between the presence of Imperata cylindrica and the low phosphorus content available in the soil. In other circumstances, it is the clogging of the soil with animal organic matter (too much N and K), a sign of an anaerobic onset that leads to the development of certain plants. Other phenomena (soil compaction, waterlogging, deep ploughing, overgrazing, wildfires and deforestation) generate comparable effects and the development of a particular flora that signals to the attentive observer the degradation of certain parameters.

For example, Cyperus amabilis is a plant species characteristic of soils with temporarily moist sandy surface horizons, such as degraded ferruginous soils.

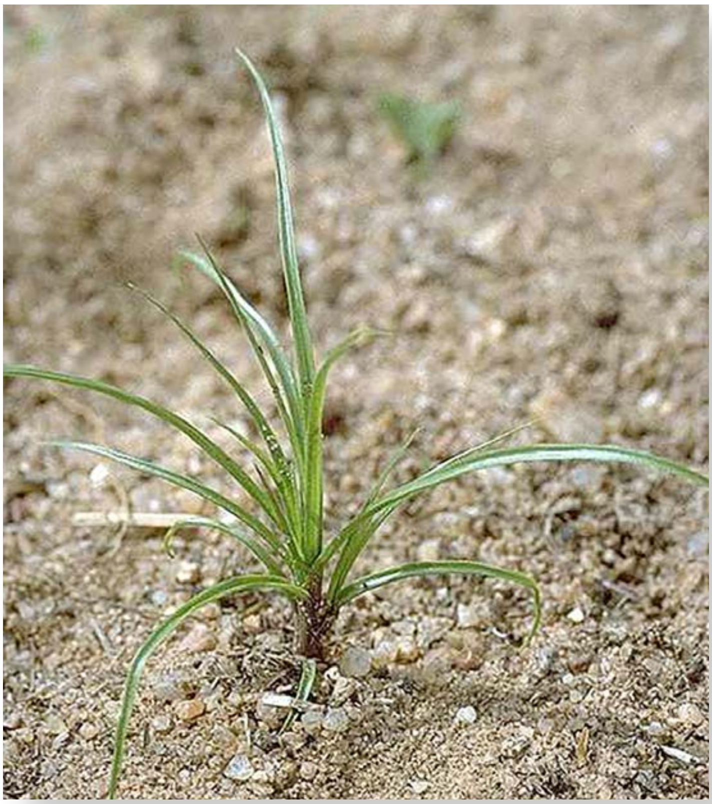


Figure 5 - Cyperus amabilis seedlings

In Ghana, farmers, when choosing the location for planting cocoa trees, prefer reddish brown plateau soils to sandy grey soils, and look for the presence of some trees on the potential site. The presence of Cylicodiscus gabunensis and Ricinodendron hendolotii is perceived as an indicator of cocoa-friendly soils, while poor soils for these shrubs are associated with Mallotus oppositifolius and Aracia pennata (FAO, 1994). Among the Fulani, plants such as Cyperus pustulatus or Crotalaria retusa have a reputation for indicating good soil fertility (they say that "these plants help to grow").

Plants can be used as indicators for factors other than fertility, such as:

- know the climate of the region;
- have an idea of the permanent or constant conditions;
- have an idea of the evolution of soil fertility;
- know the amplitudes of variation or beat (groundwater), the daily (hot days / cold nights) or seasonal alternations;
- indicate regular events (mowing, fire, grazing,…).

2.2.2.3. Analysis of plant tissue

Plant tissue analysis measures the nutrient content of plant tissues. It can usefully complement the results of the soil test. By comparing the results of the plant tissue analysis with the values considered normal for the crop in question, it can be determined whether it lacks a particular nutrient. For some nutrients, the analysis can indicate whether the soil contains enough nutrients to ensure optimal plant development. Once it has been established that a soil is sufficiently nutrient rich, plant tissue analysis can help to understand why nutrients are poorly absorbed by the plant. Plant tissue analysis can be used to assess the phosphorus, potassium, magnesium and manganese content of the soil. It is also very useful for assessing the content of boron, copper, iron or molybdenum since reliable soil analyses are not available for these elements. Plant tissue samples are calcined, then the ashes are dissolved in an acid before analysis, usually by atomic absorption spectrometry (the presence of certain elements colours the flame; the absorption of a certain wavelength is measured). This technique can be applied to the dosage of about thirty elements, both major and trace elements.

2.2.2.4. Soil analysis

In establishing a diagnosis, a laboratory analysis is a useful addition to observing the land. Soil analysis is a better method than observation of symptoms indicative of a deficiency, as it is possible to determine the nutritional needs of the plant before planting takes place. The qualities and deficiencies of the soil can be identified with a view to improving yields.

Soil is analysed to determine its nature, composition and resources. The different characteristics of the soil are established: its composition (including organic matter content), structure, pH, etc. The analysis also identifies deficiencies or excesses of nutrients so that a specific response can be provided.

The results will vary depending on the laboratory conducting the analysis, and on the way in which samples are taken. In general, an analysis report should indicates, at the very least:

- soil type
- degree of acidity: pH_{water} is a particularly useful criterion if liming in acid zones is contemplated (pH_{water} of less than 6) (see Chapter 1, note 7).
- organic carbon level (percentage of organic matter) and carbon/nitrogen ratio
- nitrogen (N), phosphorus (P_2O_5), potassium (K_2O) contents, as well as exchangeable calcium (Ca), magnesium (MgO) and sodium (Na)
- total calcium and active calcium.

Some laboratories also indicate the need for lime, or give other guidance on manure, the addition of organic material, the percentage of sand to be added to improve the soil, etc.

It is always possible to request additional analyses on:

- granulometry (particle size according to 5 fractions): Clay (0.002 mm) - Fine silts (0.02 mm) - Coarse silts (0.05 mm) - Fine sands (0.2 mm) - Coarse sands (2 mm) - Refusal (coarse elements, stones) (see Chapter 1)
- cation exchange capacity (CEC); as a reminder, CEC is used to measure soil fertility by indicating the capacity of a given soil to retain nutrients (see Chapter 1)
- copper
- iron
- sulfur
- zinc
- chlorine
- manganese
- trace elements
- compost and other organic amendments
- soil texture (percentages of sand, silt, clay)
- humus present and desirable
- metal trace elements: nickel, chrome, etc., and particularly potentially toxic elements such as lead or cadmium.

2.2.2.5. Diagnosis of soil structure and biological activity

An initial soil structure diagnosis can be performed with a few simple tests.

While producing a **soil profile** does not provide all the keys to understanding the functioning of the soil, physical observation of the crop profile is an essential step: observing the profile, determining the bedrock and origin of the soil, incorporating the climate to assess the behaviour of organic matter, etc.

Figure 6 - Direct observation of a profile in a plot
Source: Lhote, technical meeting, Centre technique interprofessionnel des fruits et légumes (Ctifl)/
Institut Technique de l'Agriculture Biologique (ITAB)

Conduct a spade test: remove a volume of soil and spread it across a tarpaulin laid on the ground. Observe the fine soil, clumps and stones on the spade and on the tarpaulin.

Count the macropores: the effect of the activities of soil macroorganisms on the structure can be assessed by counting the macropores. Using a cross-section or mini-ditch, count the macropores of diameter >3 mm at mid-depth and at depth. The depth cannot be fixed for all soils; it will depend on the soil nature and cultivation techniques. But the depth to consider should be linked with the cultivation depth and the length of roots in the biologically active part of the soil profile. The density of worm burrows is a good indicator of the quantity of earthworms present in the soil (earthworm biomass) and therefore of the biological functioning of the soil.

The density of large burrows (diameter >3 mm) indicates the activity; the density of small burrows (diameter 0.5 to 1 mm) indicates the soil's porosity (Table 2).

Table 2: Earthworm activity (large burrows)

Density: spacing between large burrows (cm)	Earthworm activity	Action
3–5	Excellent	Avoid disturbing the environment
5–10	Very good	Continue to foster this good activity
20–40	Average	Earthworm activity to be improved
50–100	Poor	Improve soil conditions that foster the development of earthworms
No large burrows	Very poor	Create soil conditions that foster the evelopment of earthworms

The density of small burrows is a good indicator of porosity, an important factor for the structural quality of soil (Table 3).

Table 3: Earthworm activity (small burrows)

Number of small burrows over 4 cm²*	Number of small burrows over 100 cm²	Estimated porosity
>40	>1,000	Excellent
20–40	500–1000	Very strong
10–20	250–500	Strong
3–10	75–250	Average
1–3	25–75	Poor
<1	<25	Very poor

* Use the counting method in column 1 or 2 depending on the time and tools available.

Count and identify earthworms: this method is based on taking a soil sample, counting and making a simplified identification of worms using illustrations (based on a guide such as Vigot and Cluzeau, 2014).

Assess the porosity of soil by measuring the time water takes to soak into the soil: this can be done using the simplified Beerkan water infiltration method (see Box).

Soil porosity is defined as the ratio between the total volume occupied by the pores (vacuums) and the total volume (voids + plenums) in a sample (see section 1.3). As porosity is complicated to measure, it is frequently assessed on the basis of one of its functions: the speed with which water seeps into the soil (Figure 61). This test is easy to carry out in practice as the equipment required is commonly available and inexpensive, and the time taken to perform the test is short compared with conventional methods. The main value of this test is to compare soil porosity over a given area or over time, for example to compare different areas within a plot of land, or changes within a given area over time.

Figure 7 - Clear the surface; insert a cylinder; pour in a quantity of water; record the time it takes to soak into the soil
Source: Lhote, technical meeting, Ctifl/ITAB

The Beerkan water infiltration method

The simplified Beerkan water infiltration method involves measuring the speed with which water seeps into the soil when it is wet, and when it is dry. A given volume of water is poured into a cylinder driven into the ground, with half of the cylinder under the surface and half above. The time required for the water poured in to seep away fully is recorded. This operation is repeated until the infiltration time stabilises.

How is it performed in practice?

Equipment: bottles, PVC cylinder 30 cm diameter and 15 cm high, lump hammer and wedge, spade, knife and bellows if the surface is not flat, scissors, plastic sheet 30 cm in diameter, metal rod for soil with rodent burrows, a stopwatch, a sheet of paper and a pen.

Time: 30 minutes to 1 hour to conduct a test (10 to 15 volumes of water for 10 to 15 measurements at a single location).

Repetitions: the test should be repeated at five or six locations in the area of interest.

Conditions: the test may be performed throughout the year. Soil porosity changes depending on various factors, some of which can be managed (date on which soil is tilled) and some not (regular activity of earthworms, growth of vegetation cover). The period in which the test is performed depends on the objectives sought. If porosity is likely to change significantly over time, several tests should be performed during the selected period. The test must be conducted on wet and dry soil, in a flat area (to avoid shrinkage cracks or animal burrows and pebbled areas). The test location also depends on the objective sought. For example, it is possible to compare a compacted area (trodden by cattle or driven over by tractors) with an area that is, in principle, less compacted, or to compare an area on a row and between rows in an orchard.

Source: ITAB (2009–11)

Assess the state of the soil surface: items to look for include crumbly structure, castings (earth thrown up by earthworms), cracking of soil, pores and burrows primarily resulting from the activity of anecic worms (those that construct deep, vertical burrows).

Figure 8 - A crumbly soil structure with numerous castings indicating intense earthworm activity
Source: Delaunois (2008)

Inspect the form and density of the roots: forked, kinked or club-shaped roots occur when roots encounter, for example, a plough pan. This is an indication of the depth and texture of the soil (Table 4).

Table 4: Significance of root density

Number of roots over 4 cm^2	Number of roots over 100 cm^2	Root density
>20	>500	Excellent
10–20	205–500	Very good: use of fertilising material in the soil (N, P, K, Ca, Mg, trace elements, etc.).
5–10	125–250	Good
5	125	Average: minimum for good use of nitrogen in the soil
2–5	50–125	Poor
1	25	Very poor: poor use made of nitrogen in the soil

Analyse the microbial biomass: this method involves treating a soil sample in the laboratory with chloroform vapours that kill almost all soil microorganisms. The content of the microbial cells enters the soil and the corresponding organic carbon can then be extracted and measured. The fumigation and extraction phases of this measurement are technically simple to perform, but specific equipment is needed to measure the soluble carbon from the samples. The results are accurate, reliable and repeatable.

Biomass analyses theoretically make it possible to:

- measure the quantity of life in soil directly
- assess the potential for mineralisation
- gauge the reserve of fertilising nutrients stored in the microbial biomass
- measure the impact of farming practices (e.g. tillage differences).

This analysis could be supplemented by the microbial activity index. But these index are strongly linked to environmental conditions (season, climate, work on the plot of land).

2.3. SOIL NUTRIENTS AND FERTILISER APPLICATION

2.3.1. Principles of applying fertiliser

Applying fertiliser is the process of providing to a crop medium, such as the soil (but also any other artificial substrate used in horticulture), the minerals necessary for plant development. Fertilisers or fertilising materials may be either chemical or organic[11]. They can be in solid or liquid form.

A fertiliser is a substance intended to provide to plants, generally through the soil, one or more minerals deemed to be insufficiently abundant in the soil to feed crops (Soltner, 1977). The objective is to obtain the best yield possible (avoiding a limiting factor), having regard to other competing factors (soil quality, climate, water supply, genetic potential of crops, means of use), and the best quality, at the lowest cost (with least economic impact, but also least impact on health and the environment).

Despite efforts made to publicise information, farmers continue to find fertiliser use difficult to master. Their customary practices are not suited to sustainable farming – for example, they do not carry out soil analysis to determine what fertilisers to apply; they apply off-the-shelf fertiliser even if the NPK ration does not fit the cultivation; they apply excess fertiliser which is washed away to pollute waterways. Farmers' actions depend on numerous factors, including the availability of organic resources (such as manure), the availability of mineral fertilisers on the market – and, of course, their purchasing power.

2.3.1.1. Role of fertilisers

In 1978, the Director of the FAO declared: "There is little virgin land to conquer. Farming growth can only come from improved yields through the use of fertilisers." Chemical and organic fertilisers play an important role in agriculture.

- Fertilisers increase yields (quantity and of quality), generating greater profits for farmers from the work they undertake and the products they use.
- They make it possible to obtain good yields from high-value crops that, without fertiliser, would not be possible. An increased choice of cultivated plant species makes it possible for farmers to adopt more productive and advantageous crop systems. Under these conditions, there are possibilities for diversifying production.

11 The fertilisers presented here are dealt with separately from soil improvers.

- Commercial fertilisers make it possible to introduce additional nutrients into the plant growth cycle and into the composition of crop residues, thus improving fertility.
- Farm manure and green manure can directly increase the organic matter content of soil, while chemical fertilisers do so indirectly by increasing the quantity of harvest residues that can be incorporated into the soil through tillage.
- Fertilisers also play a role in product quality. For example, potassium fertiliser improves the texture of potatoes when cooked and can reduce the flouriness of the flesh (Nicolardot, 2014).

2.3.1.2. Fertiliser must be applied carefully

Fertiliser use must respond to the objectives of sustainability. It must be undertaken in a considered manner, and must take account of both the economic context (cost of fertiliser, type of market targeted, legal requirements, intrinsic value of harvested product and by-products) and the environmental context (impact on the environment: air, soil and water). Farmers must identify their needs precisely, based on their farming objectives and methods. They must take into account the nature of the soil and the requirements of each crop, allowing for rotation or crop combinations, as well as the mineral or organic resources available locally, in sufficient and adequate quantity and quality (livestock manure, compost, etc.).

Based on quantitative and qualitative production objectives, farmers adjust their inputs of fertiliser to allow for the characteristics of the environment in which they work (soil, climate, proximity of surface water or capture areas). In this way, fertiliser application seeks to incorporate environmental constraints such as the preservation and restoration of water and soil quality. The aim is to provide each crop with sufficient fertiliser for its nutrition, adapting the timing of fertiliser spreading to crop needs and avoiding any excess – applying the right dosage at the right time. For example, for nitrates this means carefully determining the quantity of fertiliser and how it is spread over a parcel of land in anticipation of the crop's needs, and with the aim of limiting the risks of water pollution through run-off of surplus fertiliser. Nitrates are not retained well by the soil, so they must be added when the plant is ready to absorb them to avoid leaching into groundwater (see Figure 9).

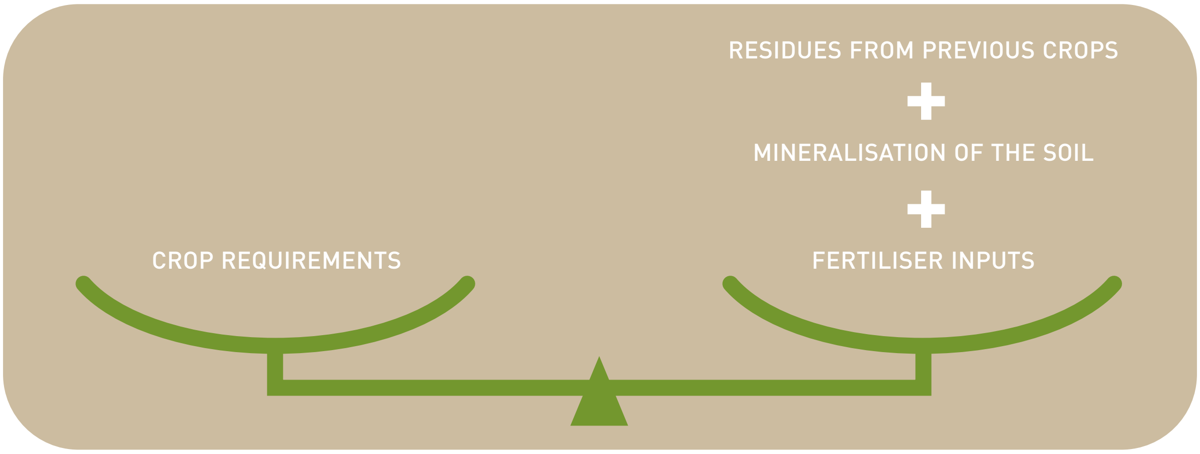


Figure 9 - Basing fertiliser inputs on needs

The types and quantities of fertiliser needed to increase crop yields and combat erosion more effectively will vary considerably depending on the soil and the crop. Responsible fertiliser use therefore calls for expertise in plant nutrition. The choice of appropriate fertilisers and the optimum level of manure will require considerable care. **Soil analyses** must be used, as must the results of experiences with manure, observations of crop sturdiness and, among others, identifying the symptoms of fertiliser deficiencies.

At plot level, determining a realistic yield objective, whether from a quantitative or qualitative perspective, makes it possible to assess the nutritional needs of a given crop and to compare those needs with what the soil can offer (the nutrient balance). The fact that these needs are rarely met in full by what the soil can offer (at least in the long term) means that there is a need for additional inputs of fertiliser from outside the plot of land, and even outside the farm. When using fertiliser it is therefore important not only to ensure the agronomic effectiveness of mineral and organic fertiliser inputs, but also to protect, or even improve, soil quality.

2.3.2. Nutrient balance and nutrient management

2.3.2.1. The nutrient import–export balance

According to Randrianarison (2016), in agriculture the **nutrient balance** is the difference between the quantity of nutrients added through organic matter and the quantity of nutrients exported by the crop, or lost for example through erosion or drainage. To prevent soil depletion there must be a trade-off between what is consumed by the crop and what is lost. In order to ensure sufficient availability for the plant, while not adding more than is necessary (leading to financial loss and ecological risks), it is useful to know exactly how much is exported (i.e. used) by the plant: this is the **export balance**. The amount exported by the crop indicates the quantity of fertiliser that must be added for the next crop (FAO, 2005). A very precise calculation of the balance is difficult to establish, but an approximation may suffice to indicate whether the quantity of fertiliser applied is too low or too high.

In practice, an overall balance consists of estimating, as precisely as possible,

- the amount necessary to ensure the level of yield sought
- the theoretical amount available in the soil.

The balance of these two values indicates the level of fertiliser to be added. Farmers should seek to add neither too much nor too little.

2.3.2.2. Mineral exports

The harvest exports only part of the minerals mobilised by the crop. What remains in the field can be retained in the perennial parts of the plants (wood, roots, etc.) or returned to the soil through root excretion, leaf fall and stalks left on the ground (Bertrand and Gigou 2000). The exports therefore depend on the yield and the parts exported (for example, for maize the nutrients are concentrated in the cobs; the 70% of the plant left in the field does not account for the 70% of the soil nutrients the plant takes up during its life cycle). Part of the elements harvested can be recycled through manures, composts, ash and other residues.

The principle for estimating exports is simple. The harvest and residues from the field should be weighed, the dry matter content estimated and the mineral content analysed. This makes it possible to calculate the quantities of elements exported in the harvest, the by-products and the residues, which can be expressed in kg/ha of elements or in fertiliser unit per ha (Randrianarison, 2016).

2.3.2.3. Deficiency and excess

When one or more nutrients are lacking, or present in insufficient quantity in the soil, the needs of the plant will not be met, its growth and development will be limited, and there will be a deficiency. The symptoms of deficiency are specific to each crop and depend on the element that is deficient (Figure 64).

Figure 10 - Symptoms of magnesium deficiency in radishes

Fertiliser inputs applied to plants in quantities that exceed their needs can be harmful and affect their growth and normal development. In practice, this occurs particularly with trace elements, of which plants need very little. The toxicity of trace elements translates into effects specific to each type and may vary from one crop to another, as does the toxicity threshold. For example, excessive molybdenum causes the shoots of tomatoes to turn yellow (Randrianarison, 2016).

Apart from the effects on the plant itself, excessive fertiliser, particularly soluble mineral nitrogen, can lead to pollution of surface water and even of groundwater (nitrates in excessive concentrations in drinking water is a serious health hazard). On the surface, nitrogen (nitrates, nitrites) and phosphorus (phosphates) from agriculture, livestock effluents, urban waste water and residues from certain industries can lead to the proliferation of algae in seas and waterways that, over time, results in the asphyxiation of the fauna and flora that live in them, leading to the 'death' of the waterway. Excessive nitrogen[12] can also make other water sources such as groundwater unfit for consumption by humans or livestock.

2.3.3. Laws governing the action of fertiliser13

To abide by the principles of sound and sustainable fertiliser management, the principles of fertiliser application must be followed. These are based on three fundamental laws. They set out, in particular, the effects of fertiliser inputs on crops (Nicolardot, 2014). The application of these three general laws and more recent knowledge acquired from agronomic research have led to better understanding of the biogeochemical cycles of such elements, and to the development of operational methods for forecasting manure inputs. Such fertiliser forecasts are being increasingly applied. Forward calculation of nitrogen inputs is an essential tool for good fertiliser management, to achieve the best possible trade-off between productivity and respect for the natural environment.

2.3.3.1. Law of replacement or advance inputs

With respect to crop rotation, this law relates to the static aspect of maintaining fertility. Mineral exports by crops and losses outside plots must be offset by replacement inputs to maintain the chemical fertility of soil. In practice, to be on the safe side, the concept of 'replacement' should preferably be substituted by that of 'advance inputs', by looking at the optimum nutrition for the crops concerned. Poor soils must be given enhanced manure to cater for the most demanding crops. In contrast, in rich soils and for crops with low requirements, phosphorus and potassium manure deficits can be managed.

However, many soils suffer from natural deficits of one or more nutrients, necessitating the input of a so-called enhanced manure prior to any intensive exploitation. Other soils need to be sufficiently fortified in organic matter or calcium to be suitable for cultivation.

Furthermore, the soil is exposed to losses of fertiliser carried off to drainage water and groundwater as a result of run-off and through erosion. Such losses are very low for phosphorus (less than 1 kg/ha/year) and low for potassium oxide (K_2O). For nitrogen (N), sulfur trioxide (SO_3) and magnesium oxide (MgO), however, they may equate to several dozen kilograms per hectare per year, and even several hundred kilograms for calcium oxide (CaO). For these reasons, determining the level of manure based solely on the level of exports is not adequate. It does, however, provide an overall approach that should be corrected in line with the richness of the soil, the various losses and peak crop requirements during the growing cycle.

12 Translated into content of nitrates (>50 mg/litre), nitrites (0.1 mg/litre) or ammonia (0.5 mg/litre). It should be noted that the content of other elements is also regulated in drinking water (e.g. the content of phosphorous [P_2O_5] <5 mg/litre, but also copper, zinc, manganese, fluorine, etc.) (WHO recommendations).

13 Also see COLEACP Handbook on *Sustainable and Responsible Production*, Chapter 2.

2.3.3.2. Law of diminishing returns

"When increasing doses of a fertiliser are input into the soil, the increases in yield obtained diminish increasingly as the quantities put in are increased" (Mitscherlich's law of diminishing returns, 1819–23). This law is reflected in a curve, the 'summit' of which corresponds to the maximum possible yield. The optimum level of yield was obtained where the additional crop obtained just covered the additional fertiliser expenditure (see Figure 65). In the figure, letters A–D represent four fields with an identical soil and crop, with different amounts of the same NPK fertiliser applied to each. In this example, field C is the optimum (the value of dc – additional crop – is lower than the cost of the additional quantity of fertiliser C–D). Although the yield is the better on field D, the cost of fertiliser does is not covered by the yield increase.

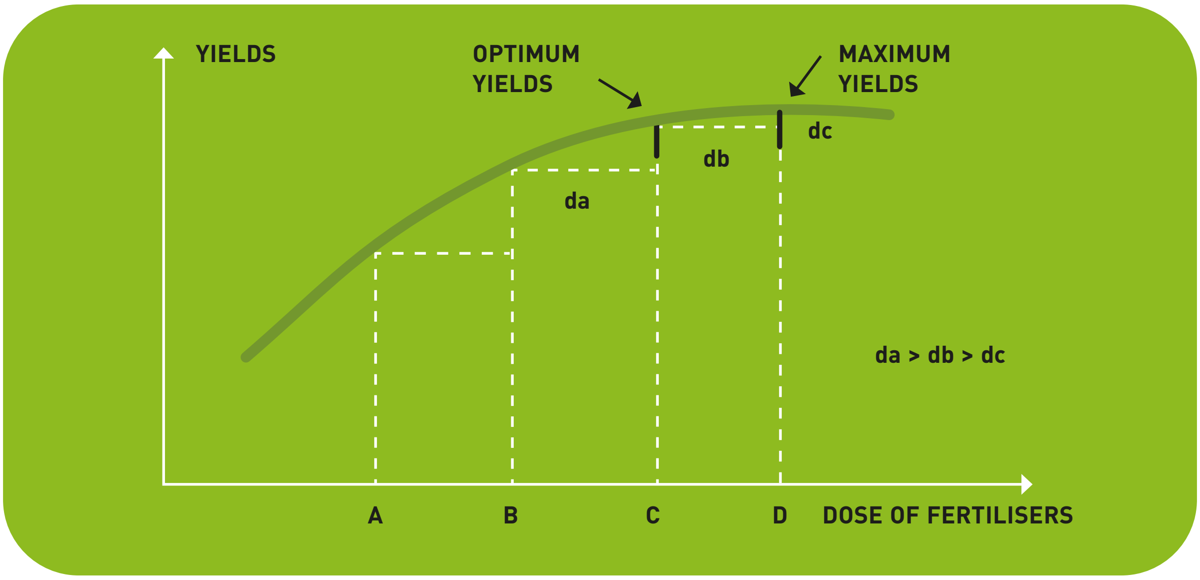


Figure 11 - Schematic representation of the law of diminishing returns

The way in which fertilisers are added may change the shape of the curve. In most cases, therefore, the addition of nitrogen in two instalments gives better results than a single input of the same field dosage rates, while providing better protection for the environment (less leaching).

2.3.3.3. Law of the minimum or of interaction

"Yield is proportional to the amount of the most limiting nutrient, whichever nutrient it may be" (Liebig's law of the minimum, 1840). In a soil with a mineral imbalance, the crop yield is therefore limited to the level dictated by the element that is present in the lowest quantity, even if all the other elements are present in sufficient quantity. Soil analysis generally makes it possible to identify the limiting factor.

Figure 12 - Illustration of Liebig's law

This law highlights the interdependence between the various nutrients and the need for them to be at their optimum balance within the soil–plant system. Such interactions exist between all production factors: nitrogen and irrigation, nitrogen and weed control, nitrogen and fungicides, fertiliser inputs and soil structure, etc.

With regard to fertilisers, an interaction is also likely to emerge:

- **in the soil**: certain forms of elements facilitate the mobilisation of other elements; for example, ammonium sulfate and ammonium nitrate contribute to the solubilisation of phosphorus pentoxide (P_2O_5) in alkaline soils
- **in plant mineral nutrition**: the absorption of part of the nitrogen in the form of ammonia (NH_4) fosters take-up of phosphorus pentoxide (P_2O_5) by plants.

2.3.4. Principles of integrated soil fertility management (ISFM)

Over the past three decades, the perception underlying nutrient management in crop systems in sub-Saharan Africa has evolved significantly in favour of more expert knowledge based on detailed in-depth field research and on changes in the general social, economic and political environment in the region. In the 1960s and 1970s, particular attention was paid to the use of mineral fertilisers to provide adequate nutrition for crops and a better yield. In the 1980s, there was increasing focus on the use of organic resources, partly due to the problems of gaining access to fertilisers in sub-Saharan Africa at that time. Today, significant research has shown the importance of combining the use of mineral fertilisers with organic matter in order to adapt to local conditions and obtain satisfactory yields while making efficient use of fertilisers. This is the essence of integrated soil fertility management (ISFM) (Fairhurst, 2015; see Table 5). Fertiliser and organic matter are not in opposition to each other, but complement one another.

Table 5: Changing soil fertility management paradigms for tropical soils over the past five decades

Period	Approach	Role of fertiliser	Role of organic inputs	Experience
1960s and 1970s	Use of external inputs	Use of fertilisers alone deemed to be sufficient to improve and maintain yields	Organic resources play a minimal role	Limited success due to deficiencies at infrastructure level and political level, and regarding crop systems
1980s	Use of organic inputs	Fertilisers play a minimal role	Organic resources are principal source of nutrients	Limited adoption; production of organic matter requires cattle, large land holdings and manpower
1990s	Combined use of fertilisers and organic residues	Use of fertilisers essential to overcome principal constraints linked to nutrients	Organic resources are principal entry point for soil fertility improvements, and play other roles in addition to the input of nutrients	Localised adoption for specific crops
2000s	Integrated soil fertility management	Fertilisers are the principal entry point for increasing yields and inputting the necessary organic resources	Organic resources may improve efficacy of fertiliser use	Objective is adoption on a large scale

Source: Fairhurst (2015)

Scientific evidence indicates that, on the impoverished soils of sub-Saharan Africa, production cannot be increased without adding nutrient inputs into fields, whether in the form of animal manure or mineral fertilisers. Management of these inputs must, however, be based on rational agronomic, ecological and economic principles.

It would take an entire handbook to describe ISFM. This volume is limited to setting out the key principles and reviewing specialist works such as *Le Manuel de la Gestion Intégrée de la Fertilité des Sols* by the Africa Soil Health Consortium (Fairhurst, 2015), the source of the following guidelines.

Integrated soil fertility management may be defined as "a set of soil fertility management practices that necessarily include the use of fertiliser, organic inputs and improved germplasm[14] combined with the knowledge of how to adapt these practices to local conditions, aiming at optimising the agronomic use efficiency of the applied nutrients and improving crop productivity" (Fairhurst, 2015). It therefore consists of the combined use of appropriate interventions on soil management, fertiliser use and crop agronomy to drive the main outputs of increased yield and productivity.

The introduction of interventions (rotation or intercropping, tillage, soil conservation, farmyard manure usage, crop residue management, fertiliser application timing, choice of cultivated varieties, water management, pest management, etc.) is affected by market economics and government policy. When such interventions are introduced successfully, productivity is increased and less land is needed to achieve a given level of production. The result is a sustainable improvement in food security, increased farm incomes and lower food prices, which benefit the urban population.

2.3.5. Fertilisers

Fertilisers are concentrated sources of essential nutrients in a form that can be easily assimilated by plants.

Depending on the number of major elements added, mineral fertilisers are of two main types.

- **Simple fertilisers** providing just one of the three primary nutrients. They may also contain certain secondary nutrients, including calcium (Ca), sulfur (S), trace elements, etc.
- **Compound fertilisers** providing two or three nutrients at the same time. These may be binary fertilisers – e.g. nitrogen and phosphorus (NP), nitrogen and potassium (NK), phosphorus and potassium (PK); or ternary fertilisers – e.g. nitrogen, phosphorus and potassium (NPK). They are formed from mixtures of simple fertilisers, or are obtained from the interaction of raw materials. Compound fertilisers are designated by a formula consisting of three numbers that represent, in the order N-P-K, the quantity of each of these nutrients contained in 100 kg of solid fertiliser (or in 100 litres of solution in the case of liquid fertilisers).

Fertilisers come in various forms: as solids (granules, crystals, grains, pearls or powder); as solutions (nitrogen solution, binary solution, ternary solution); or in the form of liquefied gas. Most commonly, fertilisers are supplied in a solid state.

Organic fertilisers come from raw materials of animal or vegetable origin. Some of these raw materials can be used on their own without being converted, or after simple desiccation or grinding. They include cow pats, dried poultry droppings, dried blood, fish meal, bone meal, crushed or roasted horns and guano. These fertilisers are not

14 A variety or seedling capable of responding to plant nutrients (varieties differ in their capacity to respond to nutrient input); adaptation to the local environment (soils, climate); and resistance to pests and diseases.

soluble in water, but most of the nutrients they contain are rapidly mineralisable and available to plants. They primarily provide nitrogen, phosphorus and potassium, but also sulfur, calcium, magnesium and trace elements.

Green manures are cover crops that produce biomass during their life cycle while covering the soil surface (see Chapter 5). They are usually non-woody green plants (or parts of plants) that grow after, or at the same time as, the principal crop; a weed derived from the fallow period; or leaves from a tree or shade plant that has been trimmed or has fallen. Preference is generally given to leguminous plants (Fabacae). In Africa, various species of annual leguminous plants with inedible seeds, such as velvet bean (*Mucuna pruriens*), kudzu (*Pueraria phaseoloides*) or lablab (*Lablab purpureus*), are used as cover crops to control water erosion, combat weeds and restore soil fertility. There are many advantages to using leguminous plants as green manure or cover crops:

- they enrich the soil with biologically fixed nitrogen gas (N_2)
- they conserve and recycle soil nutrients
- they provide protection for the soil, helping to reduce erosion
- they require little or no immediate mineral fertiliser.

The soil must be tilled at scheduled intervals to promote the establishment, maintenance and incorporation of this green manure (IFDC, 2002).

Annexes 1 and 2 present the inputs of various nutrients (N, P, K) and other principal types of fertiliser used by farmers.

Mineral fertilisers are often less costly than farmyard manure in terms of the cost of the nutrients they contain (cost per kg of nutrient), or than compost, but they are often considered costly by farmers as they must be paid for in cash. In Africa, although the majority of farmers quite rightly see fertilisers as being very expensive (in Benin, for example, the cost of fertilisers can amount to up to 70% of cultivation costs), some farmers add excessive mineral fertilisers to their vegetable crops, sometimes resulting in acidification of the soil.

The price of mineral fertiliser has increased following the removal of subsidies. Fertilisers are currently more expensive in the majority of sub-Saharan African countries than anywhere else, essentially due to the lack of effective infrastructures for the fertiliser market and poor transport networks. In 2006, in the Abuja Declaration on Fertilizer for the African Green Revolution, adopted at the African Union's Africa Fertilizer Summit, decision-makers wished to increase the level of use of fertilisers from an annual average of 8 kg of nutrients per hectare (in 2006) to at least 50 kg/ha (for 2015); reduce the purchase costs for fertilisers at regional and national level; and improve farmers' access to fertilisers by developing and expanding input distributor networks and local community networks in rural regions. It should be noted that these objectives are still far from being achieved.

2.3.5.1. Fertiliser success factors

Plants take minerals from the soil to produce organic compounds. It has been established that several nutrients are necessary for normal plant functioning. In addition, nutrients must be available and present in a form that can be assimilated by plants so that they can be absorbed by the roots.

Successful use and combination of chemical and organic fertilisers depends on a number of factors.

- A satisfactory balance must exist between the principal **uses of the land** (forests, pasture and crops), taking into account the characteristics of the soil, the farm and the need to balance the production of agricultural businesses.
- A carefully considered **crop plan** is required; in some places a plant can grow for several consecutive years on the same land, but the best results are generally obtained by using crop successions or rotations, which may include leguminous crops with deep roots, or mixed crops of two or more plants.
- **Tillage frequency** must be aimed at preparing the soil for seeding in an appropriate way at the appropriate time, making the soil more permeable to water by incorporating organic matter, chalk and fertilisers deep down and as needed, and by destroying weeds.
- A procedure must be adopted for the conservation and use of **organic matter**.
- The **system for fertiliser use** must be chosen at the same time as the other practices, in order to ensure the most satisfactory crop combination and obtain high yields. In particular, this system must take into account all the crops forming part of the rotation or mixed crop, as well as the resources resulting from the use of manures.
- On acid soils, **liming** is generally a prerequisite necessary to enable a range of crops to be grown and for the soil to acquire the characteristics that favour the use of nutrients. Lime must be applied carefully as excessive liming has a detrimental effect on the assimilation of nutrients.

The long-term results of agronomic trials undertaken in various countries show that certain nutrients in the soil may be diminished when there is an imbalance in the fertilisers used; for example, when large quantities of nitrogen fertilisers are applied without the requisite quantities of fertilisers containing potassium, phosphorus and other nutrients. These problems can be corrected or predicted by ISFM, which stresses that mineral fertilisers should be used in fields where they can produce a better effect within a single farm.

2.3.5.2. Chemical elements essential for plant nutrition

Over 100 chemical nutrients are known today, but only 17 are seen as essential to plant growth and development. Of these 17 essential chemical nutrients, carbon, hydrogen and oxygen are taken from air and water. The other 14 are normally absorbed from the soil by plant roots, and fall into three categories:

- primary essential nutrients: nitrogen, phosphorus and potassium (N, P, K)
- secondary nutrients: calcium, magnesium and sulfur
- trace elements: iron, zinc, manganese, copper, boron, molybdenum, chlorine and nickel.

An essential nutrient must have the following characteristics:

- in its absence the plant cannot complete its life cycle, even if all other elements are present and the environment is favourable
- it cannot be substituted

- one or more essential metabolic reactions must be directly involved
- when incorporated in the crop medium (injected or pulverised) it must result in the disappearance of symptoms of foliar deficiency or other symptoms attributed to its absence and bring the plant to its maximum growth, subject to the limits imposed by the physical and other factors present.

The diversity and importance of the functions fulfilled by mineral nutrients confirm the need to ensure that they are available in sufficient quantities for optimum crop production.

Table 6: Nutrients, their forms of absorption and functions

Nutrient	Forms of absorption	Principal functions
Nitrogen	NO_3^-, NH_4^+	Constituent element of the principal compounds of cells, proteins, chlorophyll and genes.
Phosphorus	$H_2PO_4^-$, HPO_4^{2-}	Constituent element of genes, central role in transfer of energy in the plant and in metabolism of proteins.
Potassium	K^+	Helps in osmotic and ionic regulation; important for several enzymatic functions and in metabolism of proteins and carbohydrates.
Calcium	Ca^{2+}	Involved in cellular division; plays a major role in maintaining membrane integrity.
Magnesium	Mg^{2+}	Constituent element of chlorophyll and a factor in several enzymatic reactions.
Sulfur	SO_4^{2+}	Constituent element in proteins, amino acids and vitamins; necessary for the production of essential oil plants.
Iron	Fe^{2+}	Constituent element of a number of enzymes such as cytochrome and ferredoxin; involved in fixing of nitrogen and photosynthesis.
Zinc	Zn^{2+}	Necessary for correct functioning of a number of enzymatic systems important for synthesis of nucleic acids, and in metabolism of auxin.
Manganese	Mn^{2+}	Component element of a number of enzymes such as those involved in photosynthesis.
Copper	Cu^{2+}	Component element of a number of enzymes necessary for photosynthesis.
Boron	H_3BO_3	Plays an important role in the migration and use of carbohydrates; involved in meristematic growth.
Molybdenum	MoO_4^{2+}	Required for normal nitrogen assimilation; necessary for fixing nitrogen and for chlorophyll.
Chlorine	Cl^-	Essential for photosynthesis and plant osmotic regulation that occurs in saline soils.
Nickel	Ni^{2+}	Constituent element of the enzyme urease in leguminous plants; necessary for plants to complete their development cycle.

2.3.5.3. Nitrogen (N)

Forms of nitrogen in the soil

Nitrogen can be found in the soil in both organic and inorganic forms. Nitrogen is assimilated by plants in the form of a nitrate (NO_3^-) or as ammonium (NH_4^+).

Plants can use both forms (nitrate and ammonium) at the same time in their growth process, but the largest proportion of the nitrogen absorbed by plants is in the form of nitrate. This ion is mobile and circulates with the soil solution to the plant roots. Under certain conditions of temperature, aeration, humidity and pH, soil microorganisms change all forms of nitrogen into nitrate.

The **organic** form represents almost 95% of the total nitrogen in the soil, for example in the form of organic matter. This nitrogen is gradually mineralised through the action of microbial flora (1–2% per year) and at the end of this process changes into nitrate (NO_3^-).

The **inorganic** forms found in soil are made up of nitrate (NO_3^-), ammonium (NH_4^+), nitrogen gas (N_2) and nitrogen oxide (NO_2). Mineral nitrogen is found primarily in the form of ammonium and nitrate; the fraction of mineral nitrogen in the soil represents less than 5% of total nitrogen. The ammonical form (NH_4^+) is the result of the first transformation of organic nitrogen in the soil. This form is soluble in water and retained well by the adsorbent capacity of the soil; it is transitional and will then be transformed into nitric nitrogen. Nitrate (NO_3^-) is the form most accessible to plants, but is also the most mobile in the soil and therefore the most leachable (with possible contamination of the water table).

The absorption of ammonium or nitrates depends on the environmental conditions. The ammonium ion may inhibit the absorption of nitrates. When both forms are present in equal concentrations, the absorption of ammonium by wheat seedlings generally exceeds that of nitrates. The absorption of either form depends on the species and the age of the seedling. Cereals prefer the ammoniacal form during the initial phases of their growth.

Sources of nitrogen

- **Soil**: The first source of nitrogen used by plants is the soil. In the absence of any fertiliser inputs, plants that do not fix nitrogen use the nitrogen from the soil during their physiological cycle. Even plants that fix atmospheric nitrogen first use the nitrogen in the seed and soil during their initial growth phase. The organic matter in the soil liberates the nitrogen usable by plants through mineralisation.
- **Organic fertilisers**: Organic residues left on the ground after harvests constitute temporary litter. In traditional farming systems in West Africa, about half of harvest residues are consumed by animals during the dry season. When they are dug in at the start of the season, these residues enrich the light fraction of the organic matter in the soil. Organic amendments (soil improvers) incorporated into the soil in the form of manure or compost, as well as green manures, also enrich the light fraction and are a source of nitrogen and humus.

- **Mineral fertilisers**: Nitrogen in the soil and organic amendments alone are not sufficient to achieve optimum yields. Mineral nitrogen fertilisers are used as supplementary nitrogen to increase yields and intensify plant production. The use of mineral fertilisers is relatively low in West Africa. Compared with developed countries and other developing countries where annual doses of mineral fertiliser can be as much as 500 kg/ha, agriculture in sub-Saharan African countries uses less than 10 kg/ha of mineral fertilisers. About 80% of fertilisers used in sub-Saharan Africa are imported, and the principal cause of this low fertiliser usage is their relatively high cost compared with the low income of farmers.
- **Nitrogen-fixing plants**: The majority of biosphere nitrogen is found in the atmosphere. Most leguminous plants primarily use nitrogen from the atmosphere through symbiosis with atmospheric nitrogen-reducing bacteria. Tropical leguminous plants, such as cowpeas (*Vigna unguiculata*), peanuts (*Arachis hypogaea*) and soya (*Glycine max*) can fix 32–89%, 22–92% and 0–95%, respectively, of their nitrogen needs in the atmosphere. The quantities of nitrogen fixed vary greatly from one species to another and within the same species because symbiotic activity is affected by the bacterial layers, the plant species and environmental factors.

Deficiency and abundance of nitrogen in the plant

Nitrogen is a nutrient that is fundamental for plant development: it is the principal constituent for chlorophyll and proteins, and stimulates plant growth. In the event of nitrogen deficiency, plants are stunted; the leaves stand up, become more rigid and turn light green; and the petiole and veins are more pronounced due to delayed development of the succulent parts. The oldest leaves turn yellow then fall off. Stems may sometimes turn red. Flowering and fruiting are also affected, with small fruits of mediocre quality that ripen early.

Figure 13 - Nitrogen-deficient strawberries

Where nitrogen is abundant, a plant has wide, dark green foliage and strong stems. The plants are succulent and very digestible and there is a reduction in the woody parts. Maturity, and consequently harvesting, are delayed as nitrogen stimulates plant growth to the detriment of the reproductive organs. Where there is excess nitrogen, plants risk being affected by heavy rainfall.

Nitrogen losses

Three phenomena result in losses and transfers of mineral nitrogen: volatilisation, denitrification and nitrate leaching.

- **Volatilisation**: Ammonium may be volatilised in the form of ammonia. The importance of volatilisation depends on climatic factors (humidity and temperature) as well as soil factors (pH, nitrogen content and organic matter). Losses are small if the soil exchange factor (cation exchange capacity, CEC) is above 20 milliequivalents (meq) per 100 g (which is the case when there is good organic matter content in the soil), and if the humidity is high. Losses are high in alkaline soils with a pH of more than 8; they are increased by alternating wetting and desiccation and a temperature above 15°C. Losses are particularly significant after spreading urea, anhydrous ammonia or livestock effluent. This is reduced by incorporation into the soil[15].
- **Denitrification**: Losses through denitrification occur in the form of volatile oxygen compounds (NO_2, NO) or nitrogen gas (N_2). The scale is difficult to assess; it is assumed that it is low (10–15%) except under anaerobic conditions. With simplified soil tillage, the conditions created will tend to accentuate this.
- **Nitrate leaching**: Water transfers, run-off, hypodermic transfer and leaching are causes of nitrogen losses. A limited fraction of organic nitrogen is carried away by run-off water, and dissolved nitric ions and ammonium may be leached. Leaching occurs primarily in cold periods when the soil retention capacity is restored, and sometimes during the growing season. The quantity of nitrogen leached depends on the soil retention capacity, the amount of water draining away and the nitric concentration of the soil solution. Nitrates are truly lost when they are out of reach of roots.

Ways of combating nitrogen losses

The principal ways of limiting nitrogen losses are:

- optimisation of nitrogen fertilisers
- splitting of inputs to apply the appropriate amounts of N at different phases of growth
- installation of plant cover during the rainy season
- digging-in of straw

15 Nitrogen pollution of the air by agriculture (including livestock rearing) principally takes the form of nitrous oxide (N_2O), ammonia (NH_3) and nitrates (NO_3). The volatilisation of nitrous oxide (or nitrogen protoxide) and ammonia is the principal way in which nitrogen is lost when livestock effluent (slurry, manure etc.), or fertilisers rich in ammonium, such as urea or ($CO(NH_2)_2$) or ammonium nitrate (a mineral nitrogen fertiliser based on ammonium nitrate, NH_4NO_3), are spread. For more information see the COLEACP Handbook on *Sustainable Air Management*.

- limitation of water inputs.

Nitrates also accompany water when it moves upwards, for example by evaporation. This phenomenon is only of real importance in a hot climate.

2.3.5.4. Potassium (K_2O)

Potassium is absorbed by plants in its **ionic form**, K^+. It is essential for the translocation of sugars and formation of starch. It is involved in osmotic and ionic regulation, as well as in the process of opening and closing stomata. Potassium is necessary for several enzymatic functions and for the metabolism of proteins and carbohydrates.

Forms of potassium in the soil

For successful potassium fertiliser management, the dynamics of potassium in the soil and its uptake by plants must be understood. In the soil, potassium is found in four principal forms that are important to plants.

- **Potassium in soil solution**: This form is directly absorbed by plants. This potassium fraction is the lowest and the most variable in the soil, and the speed of resupply of potassium in the soil solution is an intrinsic soil characteristic. When plants draw up their potassium requirements from the soil by absorption through the roots, clay soils restock soil solution with this nutrient more rapidly than sandy soils.
- **Absorbed potassium**: There is a balance between potassium in soil solution and that which is absorbed by the cation exchange complex; the two states constitute a functional whole for plant nutrition. Exchangeable or assimilable potassium corresponds to the quantity of K^+ in the soil solution and that absorbed by the cation exchange complex, which can be extracted with a solution of normal and neutral ammonium acetate. By using ammonium acetate, 95% of potassium absorbed by the soil's humic-clay complex can be extracted.
- **Potassium within crystalline networks**: This internal potassium is more difficult to mobilise for plant nutrition. This means that the K^+ ions do not remain absorbed within the cation exchange complex, but may also penetrate within between the clay platelets. This is referred to as retrograde potassium, or potassium fixed in a non-exchangeable form. But when the potassium returns to the complex, it again becomes usable by the plant: the potassium is then referred to as being regenerated. Under certain conditions, this form of potassium can contribute significantly to plant nutrition.
- **Non-exchangeable potassium**: Crystalline and volcanic forms are generally rich in potash (2–7% in granite feldspars), but this potash is in a form that is virtually insoluble and therefore cannot be used by plants. However, through the action of atmospheric agents and roots, a small fraction can be made available to plants.

Sources of potassium in the soil

Potassium may be added through fertiliser inputs, and also through crop residues (from green vegetable crops, straw, etc.), composts, livestock effluent (manure, cattle or pig slurries) and urban or industrial waste (household waste is very rich in potassium) (see Annexes). In all cases it is the K^+ cation that is introduced into the soil. Unlike phosphorus, potassium does not need microbial decomposition to become available. Potassium escapes from residues through leaching, when there is rain, before seeping into the soil. The quantity of potassium that leaches from residues depends on the rainfall. Potassium is released during the mineral alteration process, which involves the phenomena of dissolution and desorption.

Deficiency and abundance of potassium in the plant

The visual symptoms of deficiency are characterised by necrosis of the oldest leaves. The plants are therefore **poorly developed,** the growth form is limp, **leaf edges vary from yellow to brown and** the leaf blade is covered with **brown spots**. In fruit trees, the **oldest leaves are wrinkled**.

Figure 14 - Potassium deficiency in an avocado tree

Potassium is antagonistic to other cations: a level of potassium absorption in the soil that is too high translates into less absorption of calcium or magnesium. So massive inputs of potassium, together with excessive potassium content in the soil, can result in deficiencies in magnesium and calcium.

Potassium losses

- **Potassium leaching**: This depends on the soil composition: in a sandy soil, potassium leaching is relatively high, calling for potassic manure inputs that exceed crop requirements. However, in a clay soil (rich in illites and vermiculites), leaching is low as these minerals readily fix potassium. Leaching is dependent on the colloid content, the nature of the clays, potassium saturation and rainfall recorded. In tropical African regions, agricultural land is lost as a result of poor farming practices (drainage, bush fires, etc.) resulting in the loss of K^+ (Stoorvogel and Smaling, 1990).

- **Export through harvests**: this varies greatly depending on the species cultivated and the yields.

Ways of combating potassium losses

The principal ways of limiting potassium leaching are:

- splitting of inputs to apply the appropriate amounts of K at different phases of growth
- introduction of plant cover during the rainy season
- digging in straw
- limiting drainage

2.3.5.5. Phosphorus (P_2O_5)

Forms of phosphorus in the soil

In soil under vegetation, phosphorus is found primarily in mineral form: crystalline (apatite-phosphorite), amorphous (living) or colloidal. It is derived from apatite by weathering; separated from soil particles (cf. Figure 23); and is also derived from the mineralisation of organic matter.

The finer the soil texture, the higher the phosphorus content; clay contains a relatively larger amount than sand. In soil covered by vegetation, phosphorus exists primarily in organic form, released by microbial decomposition of the organic matter, and is particularly found in the arable layer, given the low diffusibility of phosphorus in the soil. Phosporus is found in several forms.

- **Insoluble phosphorus in bedrocks**: This represents the vast majority of total phosphorus in the soil, a form that is virtually unusable by plants. It is, however, the general reserve, from which a small fraction reaches the end of the chain in soil solutions after numerous slow physicochemical or biotic transformations.
- **Phosphorus linked to organic nutrients**: In this case, phosphorus is involved in more or less stable organic molecular structures that cannot be assimilated by plants. Humus is involved in phosphoric nutrition by limiting the development of phosphoric acid into forms that are more difficult for plants to assimilate, in particular in limestone soil.
- **Phosphorus linked to mineral nutrients**: Phosphoric ions can be fixed in the clay–humus complex, particularly on clays. Increasing the clay content reduces the phosphorus diffusion coefficient as a result of the increase in adsorption sites on the surface of the particles. The absorbed phosphorus (P_2O_5) represents just a small part of the total phosphorus. It constitutes the bulk of the assimilable or exchangeable phosphorus which may, depending on the soil, equate to 300–500 kg/ha. In limestone soils, soluble phosphorus ions become insoluble in

the form of tricalcium phosphates, and to a small extent in the form of apatite.

- **Phosphorus in the soil solution**: This is the smallest fraction of the total phosphate, and the one that is most important for plant nutrition. The phosphorus is found in two forms, dihydrogen phosphate ($H_2PO_4^-$) and hydrogen phosphate (HPO_4^{2-}), which are dominant in the soil solution. The solubility of phosphorus minerals and the concentration of $H_2PO_4^-$ and HPO_4^{2-} in the soil are greatly dependent on the pH.

Together, the latter two forms of phosphorus (in the soil solution and absorbed by the clay–humus complex) constitute the fraction of total phosphorus considered to be the principal nutritional reserve. This corresponds to the assimilable or exchangeable phosphorus.

Sources of phosphorus

Farmers input phosphorus through the use of organic fertilisers (phosphorus is naturally present in animal and plant waste). The mineralisation of plant residues through microbial activity increases the soil's assimilable phosphorus content (labile phosphorus and dissolved phosphorus). Only the phosphorus from the clay–humus complex is readily available (0.2–1 kg/ha of phosphorus pentoxide, P_2O_5). As it is not very mobile in the soil, it is preferable to place it precisely where plant roots can take it up.

Mycorrhizae often play a fundamental role in plants' absorption of phosphorus. By secreting enzymes, mycorrhizae can absorb phosphorus fixed by the soil (in a form not directly assimilable by plants) and then transfer it to the plant in return for sugars derived from photosynthesis (root symbiosis).

Deficiency and abundance of phosphorus in the plant

A phosphorus deficiency results in a slowing of plant growth and a purple colour in the leaves, that begins in older leaves in particular.

Figure 15 - Phosphorus deficiency on salad leaves

Phosphorus deficiency may take a benign or acute form. The benign form is reflected in an overall reduction in growth: the plant is more slender, the petiole is elongated, ribs are more pronounced and leaves are thin and erect. In the acute form, leaves turn yellow and become necrotic with rust-coloured browning (not the bronze colour seen in potassium deficiency).

Although the symptoms of excess phosphorus are rarely seen in nature, an excess is reflected in limited growth and overall chlorotic yellowing.

Phosphorus losses

In extensive farming, the annual export of is 0.5% of the total phosphorus in the arable layer of the soil, while the export of nitrogen is 1.4%. Depletion of phosphorus is therefore less pronounced than that of nitrogen. In intensive farming, exports are much higher and must be offset by a manure (e.g. farmyard manures, slurries or certain composts that are rich in phosphorus).

Phosphorus is lost from the soil in the following ways.

- **Erosion:** the organic phosphorus, the most assimilable, is found mainly in the topsoil. Erosion causes a significant loss of P and N, which may be greater in areas subject to erosion than that due to exports by crops. The fight against all erosion is necessary because subsoil P is very slowly transformed into assimilable P after erosion.
- **Lability**: When complexes are formed with phosphorus it becomes inaccessible to plants. Under tropical conditions, latosols (the name given to soils found under tropical rainforests with a relatively high iron and aluminium oxide content) contain 16–41% of the total phosphate, but can only provide 0.2–6% of the assimilable phosphate due to the formation of insoluble complexes with iron (sesqui) oxides present in these soils.
- **Leaching**: This is practically non-existent, given the very limited mobility of phosphorus in the soil. Phosphate fertilisers should be applied in the area where the roots are found, and the soil should be provided with the best biological conditions to increase the activity of microorganisms.

Ways of combating phosphorus losses

The principal ways of limiting phosphorus losses are:

- combating soil erosion
- splitting of inputs to apply the appropriate amounts of P at different phases of growth
- introducing plant cover during the rainy season
- digging in straw;
- limiting water inputs.

2.4. ROLE AND NATURE OF SOIL IMPROVERS

2.4.1. What is a soil improver?

Soil improvers are **mineral** (e.g. sand) or **organic** (compost, straw, turf) products added into soil to change its physicochemical characteristics – primarily the **structure** (how the soil constituents are brought together) and the **pH**.

The aim of adding an improver is to:

- improve the physical properties of soil
- neutralise soil acidity
- restore the absorbent complex
- maintain the flocculated colloids.

Figure 16 - Examples of soil improvers

In humid tropical regions, the soil pH tends to be low: the soil reaction tends to be acid as a result of leaching caused by heavy rainfall. Progressive soil acidification under the influence of natural processes, plant production and farming practices means that the acid base status of soil must be managed. The use of basic mineral improvers makes it possible to maintain the pH at a level compatible with satisfactory mineral bio-availability and at an optimum state for the physical component of fertility. **Liming** makes it possible to reduce or neutralise the acidity of acid soils. Crushed limestone (calcium carbonate, $CaCO_3$) is one of the most effective and cheapest products that can be used as a soil improver.

2.4.2. How to choose a soil improver

A product will act as an improver if it releases ions capable of:

- being absorbed on the complex, resulting in the desorption of hydronium protons (H_3O^+)
- neutralising the pre-existing free protons and those released
- exerting ionic 'pressure' in the soil solution that results in the flocculation of colloids.

In addition, the product must be abundant in nature to be inexpensive. Certain calcium and magnesium salts meet these characteristics. To neutralise the protons, a salt of a weak acid must be used. This means that only the following are usable: calcium and magnesium carbonates; oxides and hydroxides; and, to a lesser extent, silicates and phosphates. The role of the anion is very important. All too often, importance is given only to the presence of calcium or magnesium – but while the principal mineral improvers add calcium and magnesium, not all calcium or magnesium compounds can be used as improvers.

2.4.2.1. Calcium and magnesium soil improvers

These provide the calcium and/or magnesium (dolomite, quicklime, etc.) that plants need. A distinction is made between basic mineral improvers, which add calcium and magnesium and are the most commonly used, improving soil properties and regulating the pH; and fertiliser improvers that, in addition to acting as a neutraliser, provide crops with at least one nutrient other than calcium and magnesium.

Calcium soil improvers play a physical, chemical and biological role. Their physical role is to make the soil structure lighter, more stable, and permeable to water and air, facilitating soil tillage and root penetration. Calcium also acts on the soil's structure and stability by fostering humification and stabilisation of the clay–humus complex. Its chemical role is in regulating soil pH and favouring the exchange of ions, as well as playing a role in the reversible fixing of phosphorus. Finally, calcium and magnesium play a role in biological activity in the soil, in particular by creating advantageous conditions for soil microorganisms (mobility of exchangeable bases, neutral or slightly acid pH, good aeration, average humidity, etc.).

Adding calcium improvers equates to liming (see Chapter 5). Raw products can be used, such as crushed limestone, chalks, dolomite, marl, industrial waste (sugar refineries), plaster or gypsum, and various mineral fertilisers.

2.4.2.2. Organic (humic) amendments

These make it possible to enrich the soil with organic matter, and some also provide a large number of minerals. Organic amendments are intended to compensate for the fraction of the soil's organic matter that is mineralised each year. They enrich the soil with organic matter, improving the structure and adding nutrients for crops.

Organic amendments are **carbon compounds** of plant, or mixed animal and plant, origin, the dry content of which accounts for over 30% of the gross product. The maximum content of each of the major nutrients (nitrogen, diphosphorus pentoxide or dipotassium oxide) is 3%. The sum of the content of all three must be less than 7% of the gross product (Nicolardot, 2014). Humic amendments consist primarily of manures, slurries, liquid fertilisers, plant residues, harvest residues, green manures, fermentable household waste and sewage sludge. Not all these soil improvers are capable of improving the soil: slurries, in contrast to manures or composts, do not improve soil structure significantly. Others, such as household waste compost, may sometimes add toxic elements (such as heavy metals) and need to be used with care.

Dead organic matter for decomposition and humification falls into two categories:

- organic matter that is rich in **soluble sugars** and **nitrogen**, which decompose quickly, release a large quantity of products that can be rapidly used by bacteria, and leave virtually no humus (e.g. green manures, slurries)
- organic matter that is rich in **lignin** and with much less nitrogen, which decomposes slowly and results primarily in the creation of humus precursors (e.g. straw, straw manure).

There are three ways of inputting organic matter into soils, which correspond to the three stages of decomposition of organic matter:

- inputting **fresh organic matter** (green manures, plant residues, animal dung)
- inputting **composts** – organic matter that has undergone initial active decomposition by microorganisms (under well controlled conditions) – which are full of microbial bodies and their secretions
- inputting **humus** – organic matter in a sufficiently advanced stage of decomposition for initial molecular restructuring to lead to the creation of fulvic and humic acids.

THE TRIPLE ROLE OF ORGANIC MATTER

Energy output role

As a result of oxidation, the wealth of carbon and hydrogen in organic substances releases major quantities of energy that are beneficial to the soil's microorganisms.

Physical role

Organic matter helps to build up the soil structure: permeability, aeration, water content, exploration by the roots. In particular, research studies have shown that young organic matter plays a primordial role in the soil's structural stability. When plant residues are incorporated into the soil, they are rapidly colonised by microbial populations. The microflora, its exudates and the products of its decomposition have strong aggregating properties, and mineral particles adhere to it. Organic matter is therefore relatively protected within these aggregates. Generally, the soil water content increases in line with the organic matter content.

Nutritional role

The mineralisation process leads to the release of the structural elements that make up the organic substances such as nitrogen, phosphorus and sulfur. With regard to nitrogen, organic matter, which fixes nitrogen from the air, is the sole source of inputs in organic farming. Growing green manures and using farmyard fertiliser are the basic methods for maintaining soil fertility in organic farming. In this case, leguminous plants have a predominant place in organic rotations as a key means of improving soil fertility. See Leclerc (2001).

Source: Chambres d'Agriculture de Bretagne (2011)

Irrespective of its stage of decomposition, and irrespective of whether or not it decomposes easily, organic matter always improves the structure of the soil into which it is incorporated. Granulation appears in the upper soil horizons, resulting in crumbly soil which is easier to cultivate and better for plant to growth. The soil texture and the porosity are getting better. Incorporating organic matter results in bacterial proliferation; increases secretions by roots, which stimulates their development; and, in particular, increases the quantity of the clay–humus complex. These are factors that will, sooner or later, make the soil structure crumbly. This crumbly structure will become even more fine if, on an improved soil, grasses (especially ryegrass, *Lolium perenne*) or leguminous plants are established for one or more years.

It also has other beneficial effects: it reduces erosion, has the effect of regulating temperatures, allows the soil to store more water, and therefore contributes to major improvements in soil fertility. However, organic manure alone is not sufficient. It is often not available in sufficiently large quantities to ensure the level of agricultural production expected by farming, and must be supplemented by mineral fertiliser inputs (FAO, 2003). Due to their properties, organic fertilisers often serve as the basis for the better results gained from the use of mineral fertilisers. The combination of organic and mineral fertilisers (sometimes described as an integrated plant nutrition system) therefore creates the best conditions for plant nutrition: the organic matter, and therefore the organic fertilisers, improve the soil properties, while the mineral fertiliser provides the plants with the nutrients they require (FAO, 2003).

However, inputting nitrogen, phosphorus and potassium through farmyard fertiliser (manure, slurries, etc.) is sometimes more expensive than using mineral fertiliser. For example, nitrogen input through green manure is often more expensive than urea, but the cost is expressed in the work involved rather than financial cost. Part of the nitrogen contained in these fertilisers is made available to crops in the year after it is spread: this is the **direct effect**. The direct effect depends on the quantities of rapidly mineralisable mineral nitrogen and organic nitrogen contained in the fertiliser. The greater and more rapid the supply, the greater the effect on the plants. The direct effect is assessed based on a nitrogen–mineral fertiliser equivalence factor (total nitrogen equilibrium constant of the fertiliser). Another part will be made available slowly in the years that follow: this is the **indirect effect**.

The efficacy of **phosphorus** and **potassium** is close to that of mineral fertilisers. For phosphorus, the fertiliser equivalence factor represents the fraction of fertiliser that has the same effect on the crop as a water-soluble phosphate-based mineral fertiliser and a neutral ammonium citrate. The potassium is entirely in the form of mineral salts, more than 80% of which are water-soluble irrespective of the animal source. Its availability to crops is therefore analogous to that of a mineral fertiliser and its equivalence factor is equal to 1. The quantity spread will depend on the crop requirements, the nutritional value and the nutrient availability.

Table 7: Nitrogen, phosphorus and potassium fertiliser equivalence factors provided by organic fertilisers

Farmyard fertilisers	N	P_2O_5	K_2O
Cattle manure	0.3	1	1
Pig manure	0.3	1	1
Cattle slurry	0.7	0.85	1
Pig slurry	0.5	0.85	1
Compost	0.1	1	1

Source: Schwartz and Dao (2005)

Measuring fertilising values in manures

For manures there is currently no method for rapid analysis of nitrogen value, and laboratory analysis is the only method available. The analysis should relate to the percentage of dry matter, total nitrogen, phosphorus and potassium.

The difficulty arises from the sampling of manure, which must reflect the composition of the manure present. If several types of manure are used, preferably an analysis of each of them should be made.

The best **manure samples** are obtained when it is spread. Place some 20 pieces of plastic sheeting on the ground. Spread the manure on these sheets (with a spreader if available), and gather the manure on top of the sheets into a bucket. Mix the matter in the bucket before making up a 1 kg sample. This should be sent quickly to the laboratory or held in cold storage awaiting transport. This simple method is easy for farmers to use.

2.5. ROLE OF THE AQUEOUS PHASE IN SOIL FERTILITY

2.5.1. Water available to the plant – useful water

Nutrients are recovered effectively by plants only if the crops have sufficient water available to them[16]. Thanks to various techniques (e.g. land planning to foster infiltration of water into the soil), it is possible to increase the quantity of rainfall captured and made available to crops in areas that are subject to drought.

The sustainable approach is aimed primarily at collecting as much water as possible to meet requirements, rather than adding water by irrigation. Water can be collected, for example, by installing structures that reduce run-off, for example the zai pits system used in the Sahel or the use of seeding reservoirs in southern Africa, to slow the speed with which water runs off the soil. Or the soil surface could be covered with an organic mulch to promote infiltration and reduce evaporation from the soil surface.

16 For more details see COLEACP Handbook on *Sustainable Water Management*, Chapter 3.

2.5.2. Role of water in transfer of ions between solid and liquid phases

Water is both a **nutrient** (source of hydrogen and oxygen) and a **vehicle** that allows roots to absorb dissolved fertilisers.

For the most part, plants take the water and mineral salts they require from the soil. The roots that form the root system and the absorbent hairs on the youngest roots play a key role in this. The roots absorb minerals in the form of ions, either from the soil solution (whether they are free or trapped in specific organic complexes or chelates), or from the soil's colloidal networks (clay–humus complex) on which nutrients are absorbed (fixed on the surface), as shown in the figure.

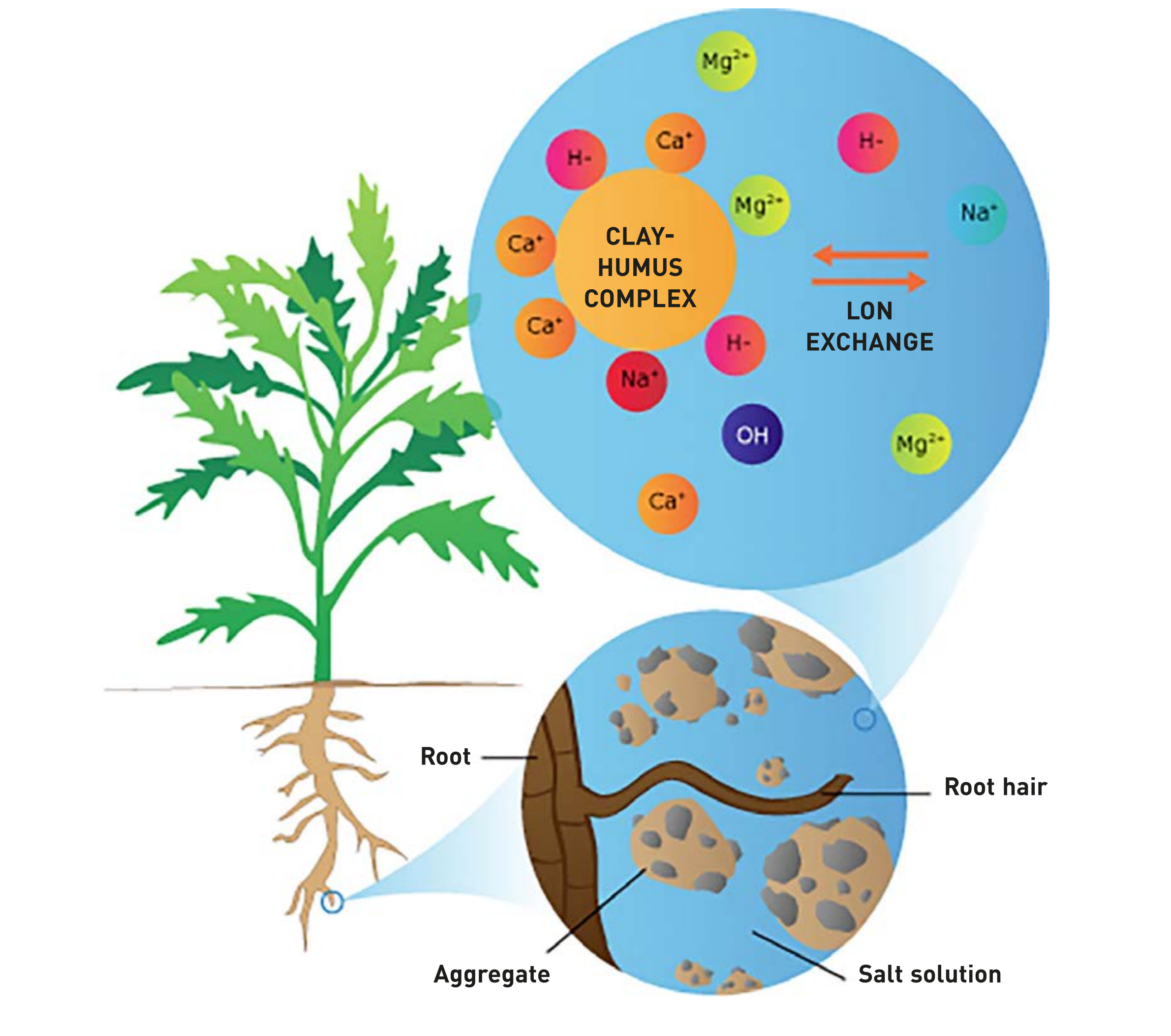


Figure 16 - Ion absorption by plant roots

The plant absorbs the soil solution (i.e. water and mineral salts) through its absorbent root hairs, and this constitutes the raw sap, or mineral sap. The soil must be sufficiently humid to enable mineral fertilisers and the mineral compounds produced by the soil organisms to be absorbed.

The minerals absorbed from colloids or dissolved in the soil solution pass to the root by two processes.

- **Mass flow**: Transport by the plants' transpiration water. This phenomenon makes quantities of nutrients that vary depending on the soil solution concentration available to the plant, and are unrelated to the plant's exports of each of the nutrients concerned.
- **Osmosis**: Movement of ions under the effect of a concentration gradient (diffusion). This depends on the absorbent capacity of the soil and the mobility of the ions. It occurs only over short distances.

The absorption of minerals by the roots is a selective phenomenon: the plant selects the nutrients that are the most useful for its metabolism. It consists of:

- a **passive ion exchange phase** on the root exchange surfaces – cations are exchanged for the hydrogen ions (H^+) of the carrier cell walls as a result of their biochemical constitution, of negative charges determining CEC.
- an **active penetration phase** that arises from the energy provided by respiration – the transport of each ion is undertaken by a specific transporter.

This explains why certain plants have a tendency to accumulate certain metal trace elements or nitrates.

2.6. ANNEXES

2.6.1. A1. Input of the principal chemical fertilisers in terms of nutrients, depending on quantities

These tables make it easy to see what is the input is (or is not) for each nutrient, depending on the quantities added (in kg, from 10 kg to 10 tonnes) on the plot of land. For intermediate values, the values just need to be multiplied or added together.

NPK 6-12-12							
QUANTITY (kg)	NUTRIENT CONTENT (kg)						
	N	P_2O_5	K_2O	MgO	CaO	Na_2O	SO_3
10	0.6	1.2	1.2				
20	1.2	2.4	2.4				
50	3	6	6				
100	6	12	12				
200	12	24	24				
300	18	36	36				
400	24	48	48				
500	30	60	60				
600	33	72	72				
700	42	84	84				
800	48	96	96				
900	54	108	108				
1,000	60	120	120				
2,000	120	240	240				
3,000	180	360	360				
4,000	240	480	480				
5,000	300	600	600				
6,000	360	720	720				
7,000	420	840	840				
8,000	480	960	960				
9,000	540	1,080	1,080				
10,000	600	1,200	1,200				

NPK 10-20-20							
QUANTITY (kg)	NUTRIENT CONTENT (kg)						
	N	P_2O_5	K_2O	MgO	CaO	Na_2O	SO_3
10	1	2	2				
20	2	4	4				
50	5	10	10				
100	10	20	20				
200	20	40	40				
300	30	60	60				
400	40	80	80				
500	50	100	100				
600	60	120	120				
700	70	140	140				
800	80	160	160				
900	90	180	180				
1,000	100	200	200				
2,000	200	400	400				
3,000	300	600	600				
4,000	400	800	800				
5,000	500	1,000	1,000				
6,000	600	1,200	1,200				
7,000	700	1,400	1,400				
8,000	800	1,600	1,600				
9,000	900	1,800	1,800				
10,000	1,000	2,000	2,000				

NPK 20-10-10							
QUANTITY (kg)	NUTRIENT CONTENT (kg)						
	N	P_2O_5	K_2O	MgO	CaO	Na_2O	SO_3
10	2	1	1				
20	4	2	2				
50	10	5	5				
100	20	10	10				
200	47	20	20				
300	60	30	30				
400	80	40	40				
500	100	50	50				
600	120	60	60				
700	140	70	70				
800	160	80	80				
900	180	90	90				
1,000	200	100	100				
2,000	400	200	200				
3,000	600	300	300				
4,000	800	400	400				
5,000	1,000	500	500				
6,000	1,200	600	600				
7,000	1,400	700	700				
8,000	1,600	800	800				
9,000	1,800	900	900				
10,000	2,000	1,000	1,000				

NPK 22-11-11							
QUANTITY (kg)	NUTRIENT CONTENT (kg)						
	N	P_2O_5	K_2O	MgO	CaO	Na_2O	SO_3
10	2.2	1.1	1.1				
20	4.4	2.2	2.2				
50	11	5.5	5.5				
100	22	11	11				
200	44	22	22				
300	66	33	33				
400	88	44	44				
500	110	55	55				
600	132	66	66				
700	154	77	77				
800	176	88	88				
900	198	99	99				
1,000	220	110	110				
2,000	440	220	220				
3,000	660	330	330				
4,000	880	440	440				
5,000	1,100	550	550				
6,000	1,320	660	660				
7,000	1,540	770	770				
8,000	1,760	880	880				
9,000	1,980	990	990				
10,000	2,200	1,100	1,100				

NPK 11-22-16							
QUANTITY (kg)	NUTRIENT CONTENT (kg)						
	N	P_2O_5	K_2O	MgO	CaO	Na_2O	SO_3
10	1.1	2.2	1.6				
20	2.2	4.4	3.2				
50	5.5	11	8				
100	11	22	16				
200	22	44	32				
300	33	66	48				
400	44	88	64				
500	55	110	80				
600	66	132	96				
700	77	154	112				
800	88	176	128				
900	99	198	144				
1,000	110	220	160				
2,000	220	440	320				
3,000	330	660	480				
4,000	440	880	640				
5,000	550	1,100	800				
6,000	660	1,320	960				
7,000	770	1,540	1,120				
8,000	880	1,760	1,280				
9,000	990	1,980	1,440				
10,000	1,100	2,200	1,600				

2.6.2. A2. Input of certain organic fertilisers in terms of nutrients depending on quantities

These tables make it easy to see what the input is (or is not) for each nutrient depending on the quantities added (in kg, from 10 kg to 10 tonnes) to the parcel of land. For intermediate values, the values just need to be multiplied or added together.

CATTLE MANURE						
QUANTITY (kg)	MINERAL CONTENT (kg)					
	N	P_2O_5	K_2O	MgO	CaO	SO_3
100	0.165	0.18	0.83	0.23	0.25	0.18
200	0.33	0.36	1.66	0.46	0.5	0.36
300	0.495	0.54	2.49	0.69	0.75	0.54
400	0.66	0.72	3.32	0.92	1	0.72
500	0.825	0.9	4.15	1.15	1.25	0.9
600	0.99	1.08	4.98	1.38	1.5	1.08
700	1.155	1.26	5.81	1.61	1.75	1.26
800	1.32	1.44	6.64	1.84	2	1.44
900	1.485	1.62	7.47	2.07	2.25	1.62
1,000	1.65	1.8	8.3	2.3	2.5	1.8
2,000	3.3	3.6	16.6	4.6	5	3.6
3,000	4.95	5.4	24.9	6.9	7.5	5.4
4,000	6.6	7.2	33.2	9.2	10	7.2
5,000	8.25	9	41.5	11.5	12.5	9
6,000	9.9	10.8	49.8	13.8	15	10.8
7,000	11.55	12.6	58.1	16.1	17.5	12.6
8,000	13.2	14.4	66.4	18.4	20	14.4
9,000	14.85	16.2	74.7	20.7	22.5	16.2
10,000	16.5	18	83	23	25	18

PIG MANURE			
QUANTITY (kg)	MINERAL CONTENT (kg)		
	N	P_2O_5	K_2O
100	0.135	0.2	0.6
200	0.27	0.4	1.2
300	0.405	0.6	1.8
400	0.54	0.8	2.4
500	0.675	1	3
600	0.81	1.2	3.6
700	0.945	1.4	4.2
800	1.08	1.6	4.8
900	1.215	1.8	5.4
1,000	1.35	2	6
2,000	2.7	4	12
3,000	4.05	6	18
4,000	5.4	8	24
5,000	6.75	10	30
6,000	8.1	12	36
7,000	9.45	12	42
8,000	10.8	16	48
9,000	12.15	18	54
10,000	13.5	20	60

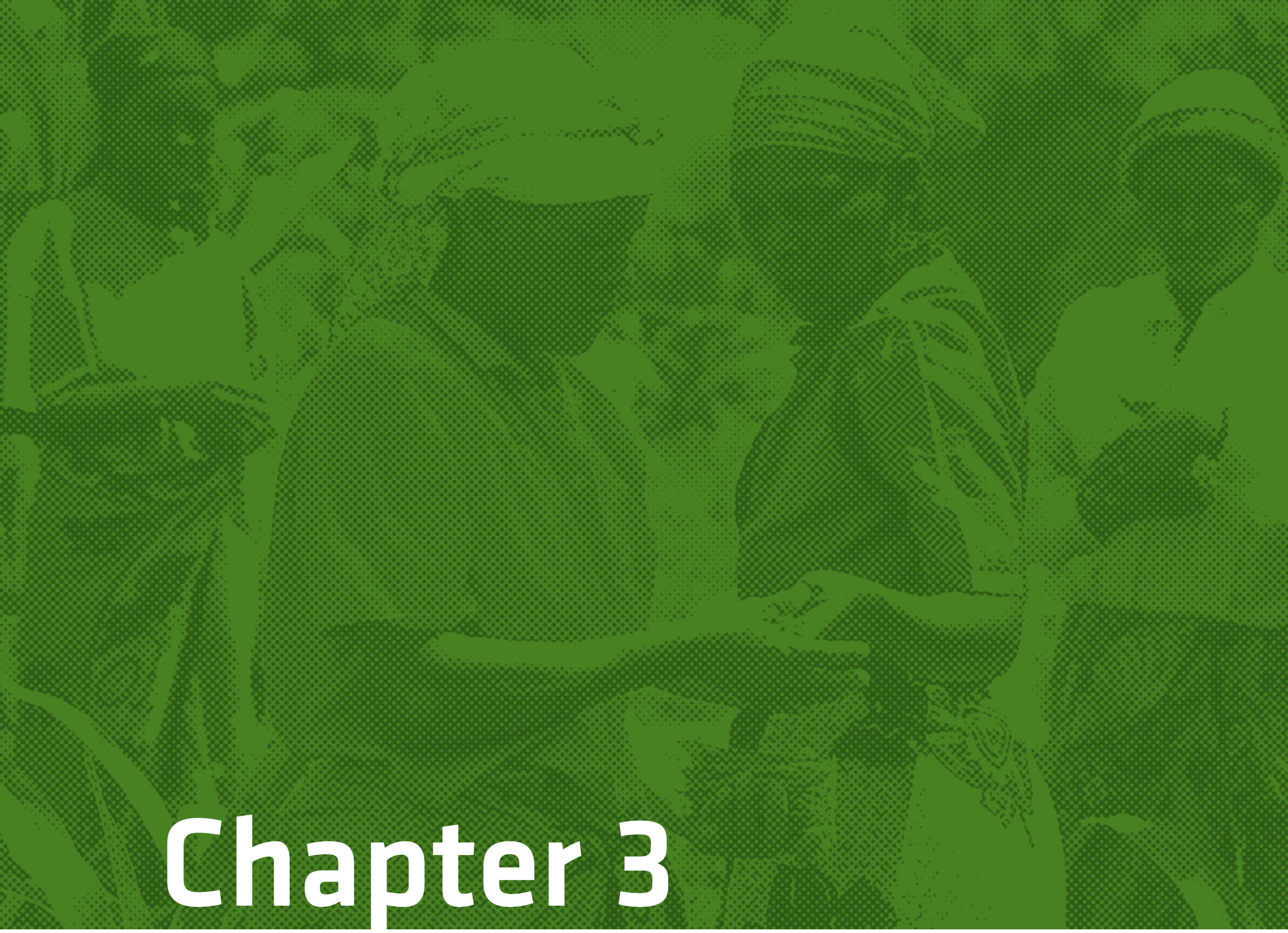
CATTLE SLURRY						
QUANTITY (kg)	MINERAL CONTENT (kg)					
	N	P_2O_5	K_2O	MgO	CaO	SO_3
100	0.231	0.187	0.33	0.1	0.2	0.08
200	0.462	0.374	0.66	0.2	0.4	0.16
300	0.693	0.561	0.99	0.3	0.6	0.24
400	0.924	0.748	1.32	0.4	0.8	0.32
500	1.155	0.935	1.65	0.5	1	0.4
600	1.386	1.122	1.98	0.6	1.2	0.48
700	1.617	1.309	2.31	0.7	1.4	0.56
800	1.848	1.496	2.64	0.8	1.6	0.64
900	2.079	1.683	2.97	0.9	1.8	0.72
1,000	2.31	1.87	3.3	1	2	0.8
2,000	4.62	3.74	6.6	2	4	1.6
3,000	6.93	5.61	9.9	3	6	2.4
4,000	9.24	7.48	13.2	4	8	3.2
5,000	11.55	9.35	16.5	5	10	4
6,000	13.86	11.22	19.8	6	12	4.8
7,000	16.17	13.09	23.1	7	14	5.6
8,000	18.48	14.96	26.4	8	16	6.4
9,000	20.79	16.83	29.7	9	18	7.2
10,000	23.1	18.7	33	10	20	8

PIG SLURRY						
QUANTITY (kg)	MINERAL CONTENT (kg)					
	N	P_2O_5	K_2O	MgO	CaO	SO_3
100	0.34	0.3655	0.45	0.13	0.3	0.07
200	0.68	0.731	0.9	0.26	0.6	0.14
300	1.02	1.0965	1.35	0.39	0.9	0.21
400	1.36	1.462	1.8	0.52	1.2	0.28
500	1.7	1.8275	2.25	0.65	1.5	0.35
600	2.04	2.193	2.7	0.78	1.8	0.42
700	2.38	2.5585	3.15	0.91	2.1	0.49
800	2.72	2.924	3.6	1.04	2.4	0.56
900	3.06	3.2895	4.05	1.17	2.7	0.63
1,000	3.4	3.655	4.5	1.3	3	0.7
2,000	6.8	7.31	9	2.6	6	1.4
3,000	10.2	10.965	13.5	3.9	9	2.1
4,000	13.6	14.62	18	5.2	12	2.8
5,000	17	18.275	22.5	6.5	15	3.5
6,000	20.4	21.93	27	7.8	18	4.2
7,000	23.8	25.585	31.5	9.1	21	4.9
8,000	27.2	29.24	36	10.4	24	5.6
9,000	30.6	32.895	40.5	11.7	27	6.3
10,000	32	36.55	45	13	30	7

COMPOST			
QUANTITY (kg)	MINERAL CONTENT (kg)		
	N	P_2O_5	K_2O
100	0.03	0.18	0.3
200	0.06	0.36	0.6
300	0.09	0.54	0.9
400	0.12	0.72	1.2
500	0.15	0.9	1.5
600	0.18	1.08	1.8
700	0.21	1.26	2.1
800	0.24	1.44	2.4
900	0.27	1.62	2.7
1,000	0.3	1.8	3
2,000	0.6	3.6	6
3,000	0.9	5.4	9
4,000	1.2	7.2	12
5,000	1.5	9	15
6,000	1.8	10.8	18
7,000	2.1	12.6	21
8,000	2.4	14.4	24
9,000	2.7	16.2	27
10,000	3	18	30

VERMICOMPOST				
QUANTITY (kg)	MINERAL CONTENT (kg)			
	N	P_2O_5	K_2O	MgO
100	0.3	0.455	1	2.7
200	0.6	0.91	2	5.4
300	0.9	1.365	3	8.1
400	1.2	1.82	4	10.8
500	1.5	2.275	5	13.5
600	1.8	2.73	6	16.2
700	2.1	3.185	7	18.9
800	2.4	3.64	8	21.6
900	2.7	4.095	9	24.3
1,000	3	4.55	10	27
2,000	6	9.1	20	54
3,000	9	13.65	30	81
4,000	12	18.2	40	108
5,000	15	22.75	50	135
6,000	18	27.3	60	162
7,000	21	31.85	70	189
8,000	24	36.4	80	216
9,000	27	40.95	90	243
10,000	30	45.5	100	270

BAT GUANO			
QUANTITY (kg)	MINERAL CONTENT (kg)		
	N	P_2O_5	K_2O
100	2.79	9.3	0.93
200	5.58	18.6	1.86
300	8.37	27.9	2.79
400	11.16	37.2	3.72
500	13.95	46.5	4.65
600	16.74	55.8	5.58
700	19.53	65.1	6.51
800	22.32	74.4	7.44
900	25.11	83.7	8.37
1,000	27.9	93	9.3
2,000	55.8	186	18.6
3,000	83.7	279	27.9
4,000	111.6	372	37.2
5,000	139.5	465	46.5
6,000	167.4	558	55.8
7,000	195.3	651	65.1
8,000	223.2	744	74.4
9,000	251.1	837	83.7
10,000	279	930	93



Chapter 3

The causes of soil degradation

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LEARNING OUTCOMES

After reading this chapter, you will:

- understand why and how soil degradation is primarily attributable to human activities, and be aware of the extent of this phenomenon
- understand the causes of declines in soil fertility (alteration of its physical and chemical properties)
- understand the phenomena of soil erosion, deforestation, salinisation and compaction
- identify the nature and origin of various soil pollutants and the danger they represent for humans, plants and the environment.

3.1. SOIL DEGRADATION IS PRIMARILY ATTRIBUTABLE TO HUMANS

3.1.1. A global phenomenon

There are numerous examples around the world of regions where soils have become seriously degraded as a result of poor use. Soil can be rapidly degraded, although it takes some 20,000 years to form and to regenerate. It is therefore essential to preserve the agricultural quality and fertility of soils. Above-ground solutions (aquaponics, hydroponics, etc.) can never fully replace the agricultural capacity of soils to produce food in the quantities required by humans, particularly in a context of high demographic growth.

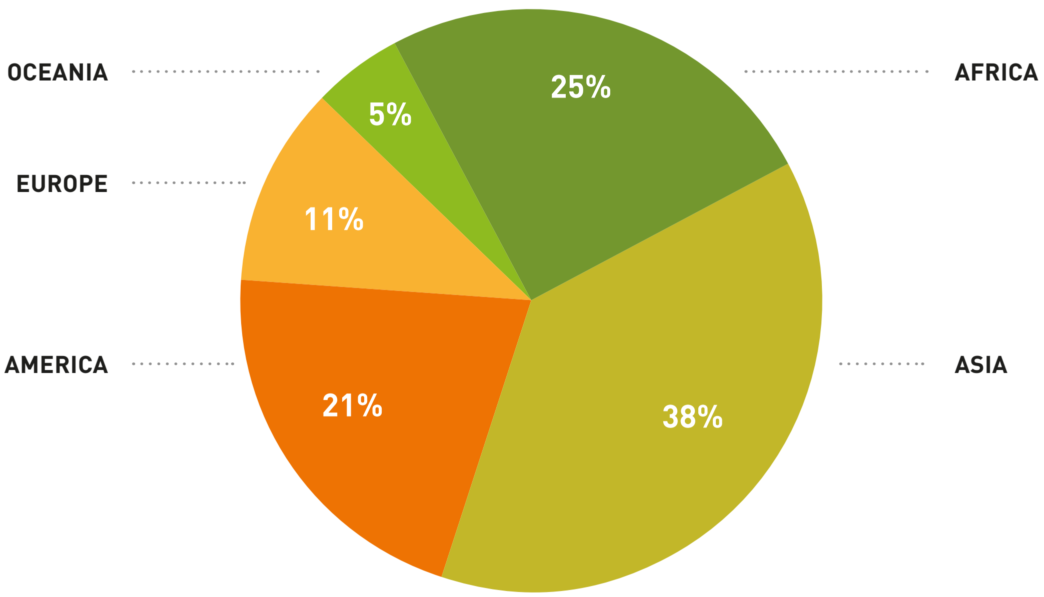


Figure 1 - Level of degradation of arable land by global region (Source: Adapted from FAO (2011))

The surface area of cultivable land is constantly declining at a rapid rate of some 5–10 million hectares a year. This is due to degradation, but also because the land is being used for purposes other than agriculture, despite its arable quality. The degradation of soil – its loss of fertility – is therefore a key economic and ecological concern throughout the world, but the consequences are felt most strongly by poor populations in developing countries. Unfortunately, soil degradation is of greatest concern where demographic growth is highest and where the food self-sufficiency of the population is at its lowest.

Figure 2 - The consequences of soil degradation are felt the most strongly by the poorest populations on the planet
Source: http://unt.unice.fr/uoh/degsol/

The principal outward signs of soil degradation fall into two groups.

- Those that currently relate to **all soils put to direct use by humans**. This includes biological impoverishment (loss of biodiversity) and decline in the levels of organic matter (loss of resilience); and also soil compaction.
- Those that are more **localised** and that, for the time being, affect relatively limited proportions of all arable surfaces around the planet. They include waterlogging (excess water), salinisation and alkalinisation, acidification, depletion of fine particles and nutrients, erosion, and pollution (with its consequences for the quality of water and agricultural outputs). Unfortunately, these areas are tending to increase, sometimes exponentially.

Soil degradation can occur at various depths, not just in the first few centimetres of topsoil (e.g. in the case of compaction or salinisation), even if the latter is generally the first and the most seriously affected.

To this must be added the disappearance of soil surfaces for urban, industrial and mining needs. We will not discuss these here, but they erode usable agricultural land, sometimes dangerously. Currently, there is **competition between the differing uses of land** – agricultural land versus land for industrial use, housing construction, roads, railways, stores with huge car parking facilities, but also competition between cash crops and food crops, export crops and crops for the local market, etc. The land question is the subject of lively debate in both developing and developed countries.

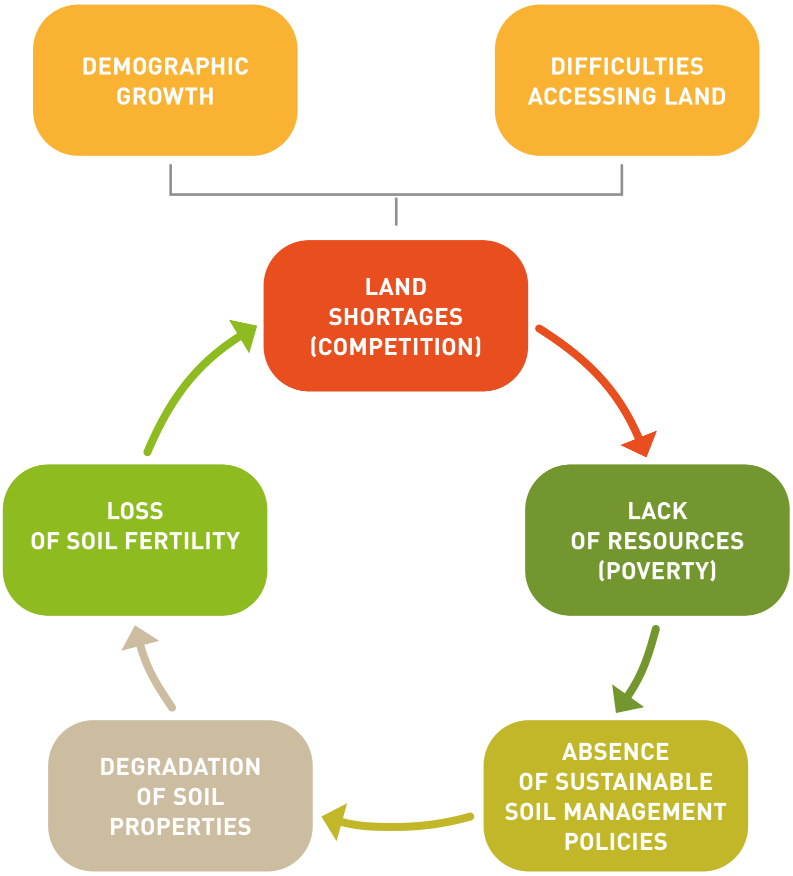


Figure 3 - The vicious circle resulting from a lack of sustainable soil management

3.1.2. The need for a preservation policy for agricultural soils

Soil is one of humanity's most precious assets: we are entirely dependent on it for our habitat and nutrition. Just one-third of the land mass is put to agricultural use (grazing, crops, forest and aquaculture)[17]. Soil is a **limiting factor** in the quantity and quality of food supply.

According to FAO (2015a), the current soil degradation rate poses a long-term threat to our ability to respond to the needs of future generations. World agriculture will need to feed nearly 9 billion individuals by 2050, with a 70% growth in demand for

17 4.9 billion hectares of agricultural land, out of a land mass of 13 billion hectares, with just 1.5 billion hectares devoted to the growing of annual or perennial crops.

agricultural products. For countries in the Southern Hemisphere, sustainable soil management is complicated by several additional challenges: demographic growth, crop intensification resulting in excessive (and often rapid) soil degradation, the absence of genuine local land management policies, the reduction in arable land, the growing demand for drinking water, competition for resources due to the expansion of urban and industrial sectors, and land management in general. Not only are these factors highly complicated, but they are also very delicate to manage due to food security problems (responding to emergencies) and poverty (lack of resources). The challenge for research and information dissemination in these countries is to increase agricultural productivity by improving and maintaining the long-term productive potential of the available natural resources (particularly soil, plants and water). Few countries have sufficient financial resources to promote sustainable soil management.

While other vital resources, such as water and air, are constantly recycled and regenerated, soil formation can take tens if not hundreds of years. In addition, soil fertility is closely linked to the range of life forms sheltered by soils, which itself depends on the organic content and quality of the soil. However, in most of sub-Saharan Africa, where soils already have fundamentally low fertility, neither organic matter nor the nutrients exported are adequately replaced. Sub-Saharan Africa has the lowest consumption of mineral fertilisers, about 10 kg of nutrients (nitrogen, N, phosphorus, P_2O_5 and dipotassium oxide, K_2O) per hectare per year, compared with an average of 90 kg at global level, 60 kg in the Middle East and 130 kg in Asia.

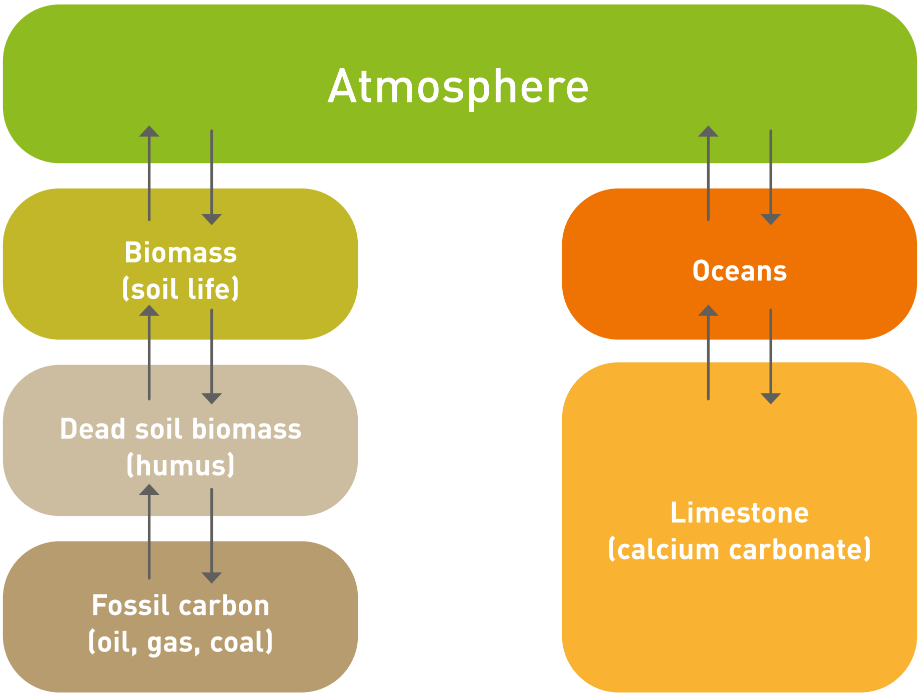


Figure 4 - Importance of soils in the carbon capture cycle:
the flows of carbon from the atmosphere are rapid and then become increasingly slow

However, not only is agricultural land the key to food security for people, it has enormous potential for **carbon capture** when it comes to the problem of global warming and the reduction of greenhouse gases. Safeguarding agricultural land and conserving soil that is fertile and thriving are thus essential issues for the planet, and are very much in the public interest.

3.1.3. Causes of decline in soil fertility

A decline in soil fertility (also described as a decline in soil productivity) can be defined as a deterioration of the physical, chemical and biological properties of the soil. The physical degradation of soil is the most significant and, for the most part, is directly related to the actions of humans (Oldeman *et al*., 1991).

Soil fertility degradation can have many causes. The principal causes are set out below, but it should be borne in mind that:

- the phenomena generally combine and mutually exacerbate their effects
- locally there may be other specific causes relating to soil properties, land management, farming practices or herd management, local climate, etc.

While farmers should manage soil with due and proper care (like all their resources), it is clear that, under economic pressure, they often adopt practices that undermine the fertility of their soils. As deterioration in fertility is often a gradual phenomenon, its effects on production are not felt immediately, but instead increase over time, leading the farmer into an impasse. Returning to a favourable situation then tends to be complicated and requires not only a reassessment of practices that have become habitual, but also heavy investments of time, labour and other aspects (e.g. purchase of manure and/or organic fertilisers, tillage, fallowing for extended periods). When it comes to soils, prevention is definitely better than cure because can become too late to act to restore sufficient fertility.

Some cultivation practices have a harmful effect on soil quality; others are favourable to maintaining fertility. This chapter focuses on the influence of cultivation practices.

Deterioration of soil physical properties

The outcome is seen in degradation of the soil structure, making it fragile, and the loss of other physical qualities of the soil (e.g. porosity). This deterioration can be explained by various factors, all of which are interlinked, including the following.

1. **Soil erosion**

   Soil erosion may be caused by humans, rainfall or wind, or a combination of all three, depending on the region, and is generated or amplified by deforestation. Soil erosion is a natural, inevitable (except in forests), but manageable phenomenon. It corresponds to the movement of sediments and organic matter from one place to another. It removes the arable layer of the soil, which is the most conducive to microbial and plant life. The materials removed (by water, which runs along the soil, or by wind, which lifts dust from the surface) may be redeposited further away without major consequences for the environment, or may contribute to diffuse pollution[18] of soils and water surfaces (e.g. contamination of waterways by pesticides fixed in soil particles). Climate and topography aside, the three factors with the greatest impact on the intensity of erosive phenomena are the nature of the soil, its properties, and the allocated use.

Figure 5 - Physical degradation of soil: the phenomenon of erosion

2. **Absence of soil cover**

Erosion is facilitated by unsuitable farming practices that leave soil bare for too long, such as tillage, weed control or overgrazing, periods of discontinuity in land use (which results in the absence of plants in the soil between crops), tillage of steep slopes, deforestation, clearance of marginal land, and slash-and-burn. Soils then lose their structure and become degraded by the action of droughts and/or the impact of rain, which washes them away instead of seeping into them. This loss of structure favours the formation of a 'surface-sealing crust' that water, air and recently germinated young seedlings cannot penetrate, exacerbating the destructive effects of water erosion. Deforestation (and its opposite, agroforestry) are not dealt with in detail here. Deforestation has many causes, including:

- the expansion of industrial farming (e.g. planting on large areas of land cleared to grow avocados in Mexico, soya in Brazil, or sesame instead of mangos in West Africa)
- 'traditional' slash-and-burn to clear plots of land before sowing

18 Pollution of the environment (contamination of air, soil and especially water supplies, wells, etc.) through drift or other movement of the product (runoff, leaching, volatilisation).

- various brush fires (including those caused by lightning)
- uncontrolled burning of pasture land to promote regeneration
- illegal logging (for charcoal, lumber, etc.)
- collection of firewood.

3. **Loss of organic matter from the soil**

   The replacement of diversified primitive (referred to as climactic) vegetation with secondary vegetation (single-cropping in the worst case) alters the formation of humus and consequently has a negative impact on the evolution of the soil's properties. There is evidence that the disappearance of diversified plant cover, and in particular trees, contributes to less organic matter being formed. The organic matter is also of poorer quality, and more sensitive to rapid mineralisation (plant residues are broken down less rapidly by soil microorganisms) and therefore to gradual depletion. The more humus lost from a soil, the greater the decline in biological activity and the more common surface sealing, compaction and erosion become, resulting in serious consequences for water quality and the production of greenhouse gases (depletion of soil organic matter due to the elimination of natural plant cover releases large volumes of CO_2, contributing to the greenhouse effect[19]). There are many reasons for the loss of organic matter:

   - the absence of plant cover and failure to return the plant residue that serves as nourishment for the biological activity of soils
   - the disappearance of biological activity, destroyed primarily by tools for tilling the soil, making it impossible for organic matter to renew itself
   - the burial of plant residues through deep tillage, which wreaks havoc on habitats and radically changes the conditions for the biological activity responsible for their degradation
   - overly rapid mineralisation fostered by intensive tillage that results in intense aeration of the soil, which catalyses the activity of the bacteria responsible for mineralisation
   - erosion, as organic matter is stored in the first few centimetres of the soil.

4. **Soil compaction**

   The phenomenon of compaction results in the appearance of flattened areas in the soil profile (e.g. the hardpan), closing the networks and galleries that slow the seeping down of water. Soil compaction may also be the result of trampling by animals or the repeated movement of heavy agricultural machinery, and leads to a reduction in soil porosity.

19 The quantity of carbon stored in soils in the form of organic matter is, on global average, three times greater than that stored in natural or cultivated vegetation. In the equatorial environment there is as much carbon in the soil as in the forest that grows on it; in environments covered by grasslands and crops there is 10 times more carbon in the soil than in the vegetation. When soil is developed by humans, much of this organic matter (up to 80%) is destroyed very rapidly – over just a few years – with the CO_2 being released into the atmosphere.

Deterioration of soil chemical properties

Chemical impairment of soils generally results in their salinisation, acidification, depletion of nutrients, pollution by industrial waste or by the application (often excessive or irrational) of pesticides or fertilisers. It makes soils unfit for farming, or even toxic (for microorganisms, soil animals, plants and even for consumers, given the excessive content of certain elements in harvests). Where soils are salinised or polluted by chemical products, soil productivity may diminish without loss of soil cover as a result of the change in chemical (and to some extent physical) properties of the soil in situ.

The deterioration of soil chemical properties can be explained by several phenomena, to which we will return later in greater detail (section 4.5).

- **Soil salinisation**: This results from the accumulation in the soil of water-soluble salts such as potassium (K^+), magnesium (Mg^{2+}), calcium (Ca^{2+}), chlorine (Cl^-), sulfate (SO_4^{2-}), carbonate (HCO_3^{2+}), bicarbonate (HCO_3^-) and sodium (Na^+). This accumulation of salts is the result of natural processes, given the high salt content of the parent material, or of the neighbouring groundwater that rises and falls with the seasons, or of human intervention through inappropriate irrigation (use of water rich in salts and with inadequate drainage).
- **Reduction in content/availability of principal nutrients and trace elements**: The loss in elements (N, P_2O_5, K_2O) was estimated at 24 kg/ha of nutrients per year (10 kg N; 4 kg P_2O_5, 10 kg K_2O) in 1990 and at 48 kg/ha per year in 2000, that is to say a loss equivalent to 100 kg of fertiliser per ha per year. Countries with the highest rates of loss (Table 17), such as Kenya and Ethiopia, also have significant soil erosion. In sub-Saharan Africa, soils have been farmed more intensively without restoring their fertility (due to limited use of fertilisers and other soil management procedures), and much of the new land put under cultivation is of poorer quality than the land cultivated previously.

Table 1: Sub-Saharan African countries classified by nutrient loss rate

Low	Moderate	High	Very high
Angola	Benin	Ghana	Burundi
Botswana	Burkina Faso	Ivory Coast	Ethiopia
Central African Republic	Cameroon	Madagascar	Kenya
Chad	Gabon	Mozambique	Lesotho
Congo	Gambia	Nigeria	Malawi
Guinea	Liberia	Somalia	Rwanda
Mali	Niger	Swaziland	
Mauritania	Senegal	Tanzania	
Mauritius	Sierra Leone	Uganda	
Zambia	Sudan	Zimbabwe	
	Togo		
	Zaire		

Source: Stoorvogel and Smaling (1990)

- **Acidification**: Soil acidification is a natural phenomenon caused by rain and by certain biological processes (respiration, oxidisation of nitrogen and organic sulfurs, etc.). But by generating exports, farming practices can accelerate the processes (e.g. planting leguminous crops, removing harvest residues). Acidification may be caused or exacerbated by intensive use of chemical fertilisers (inputs of ammoniacal nitrogenated fertilisers) or by climate changes, but also by irrigation (leaching of nitrates) and drainage. Sooner or later, depending on the buffering power of the soil pH, it leads to a fall in pH. The pH_{water} may therefore fall to values at which aluminium becomes toxic (pH_{water} <5.5) and may greatly disadvantage crop production. Measuring the pH_{water} is essential to determining the acidity of a soil. The pH_{water} must be measured every five years at the same period. For the vast majority of crops (cereals, maize, vegetables), keeping the pH_{water} within the 6–6.5 range makes it possible to overcome any problems linked to excess acidity. When the pH_{water} is >6.5, the risks of deficiencies (manganese or boron) and diseases (e.g. potato scab) increases significantly.
- **Pollution by heavy metals and toxic materials (biocides, pesticides or other pollutants such as hydrocarbons)**: Heavy metals (or metal trace elements more generally), such as lead, cadmium, zinc or copper, gradually accumulate in soils through external inputs (manures, slurries, household waste compost) and can destroy or harm the development of organisms (earthworms, insects, nematodes) or microorganisms (bacteria, fungi) essential for humification, and for maintaining the cohesion and capillarity of the soil. Pesticides and other biocides or hydrocarbons may also be found in the soil (even temporarily) in such concentrations that they destroy the life of the soil, creating an imbalance in major mineralisation cycles, or even causing a biological vacuum. The chemical balance between nutrients is disrupted, the pH changes, exacerbating the phenomenon, and at the same time the soil structure gradually changes.
- **Impacts of the use of chemical inputs**

  Pollution by organic pollutants that are released into the atmosphere and fall onto soils is a big problem. Soils store chemicals in their 'memory', especially dioxins and polychlorinated biphenyls (PCBs), which are particularly persistent pollutants in soils; polycyclic aromatic hydrocarbons (PAHs); and heavy metals such as cadmium, copper, lead and zinc. Industrial pollution is very significant around urban centres where industries and heavy use of leaded fuel have contaminated the soil with lead. Polluted soils can become unsuitable for cultivation, especially where soils are shallow (e.g. Yaoundé in Cameroon), or on the periphery of mining sites (e.g. Lubumbashi in the Democratic Republic of Congo).

  Intensive agricultural practices can also 'mark' the soil for a long time. There is a difference between soils cultivated using organic farming and those in which mineral fertilisers, insecticides, fungicides and herbicides have been used for years, where biodiversity and biological activity are reduced and the soil structure becomes weak.

Soil pollution caused by pesticides

In Africa, vegetable farmers need to improve the productivity of their agricultural land so they can maintain and even improve their incomes. This has led to an evolution in agricultural practices to incorporate the use of chemical inputs, particularly pesticides (Amadou, 2013).

Every person handling pesticides is responsible for the environmental consequences of their use. Whenever a plant health product is used, there is a risk, due to accident, negligence or lack of knowledge, that part of the product contaminates an area outside the treated area. Areas particularly at risk are wells, marshlands and streams; cultivated areas where existing or future crops may be contaminated; and uncultivated land with wild fauna and flora.

For several years, plant protection products used in agriculture have been responsible for environmental degradation, particularly noticeable in intensive farming regions.

Figure 6 - Empty pesticide packaging, left on the ground or thrown into wells in Burkina Faso (Source: D. Son)

Soil pollution caused by fertilisers and soil improvers

The dissolution of mineral fertilisers in the soil has several effects on the soil's properties, with the **salinity** and **pH** (acidification) being the most apparent. These effects vary between fertilisers. Over the year, more than 160 million tonnes of mineral fertilisers are spread onto the surface of our planet. In six decades, the use of these substances is believed to have increased fivefold and to have greatly increased the productivity of crops. But the large quantities of these fertilisers being spread in the environment are one of the main factors responsible for agricultural pollution (Hateb, 2012). As intensively cultivated farmland is naturally poor in mineral elements such as nitrogen, potassium and phosphorus, for years farmers have used chemical inputs for these elements, and in some regions we have seen levels of phosphorus in soils that are too high.

Some phosphate-based fertilisers contain pollutants such as cadmium, and organic fertilisers (e.g. slurry, pig manure) contain high concentrations of copper and zinc. Cadmium, copper, zinc and lead are also regularly found in organic amendments and fertilisers.

Deterioration of soil biological properties

Biological degradation can be explained by farming practices (e.g. mechanical tilling that buries the upper layer deep in the soil), the input of chemical products (fertilisers, pesticides), reduction in the soil's organic matter content, acidification (pH too low), combustion of the biomass and depletion of the plant cover. Climate certainly plays a role (temperature and rainfall pattern). The degradation manifests itself in a loss of biomass (e.g. reduction in the number and activity of bacteria in the soil) and in the biodiversity of the soil's (micro)flora and (micro)fauna. The key cycles (carbon, nitrogen, phosphorus) are disrupted, sometimes permanently. Finally, due to the disruption of humification, the formation of aggregates (the clay–humus complex) is also affected. The soil then loses much of its quality and fertility.

3.2. SOIL EROSION

The word erosion comes from the Latin word *erodere*, which means "to eat away". It is the stripping (process during which soil particles are detached), transport and deposit of soluble and solid elements from the soil under the effects of water erosion or wind erosion. It can be of natural or human origin (human-induced erosion caused by tilling the soil).

Erosion[20] is a natural phenomenon that can have beneficial effects – such as depositing fertile sediments – as well as harmful effects. It is therefore not necessarily desirable to stop all erosion, but it has to be reduced to an acceptable, tolerable level. It has often been presented as a major danger for soils, either because it selectively depletes the upper horizon of its vital substance (living or dead organic matters, clays, silts and nutrients), or because it strips the upper horizons, sometimes down to the rock. But erosion is also a cause of the regeneration of mountain soils and the formation of the most fertile plains. Erosion is only a problem if the soil loss impacts significantly on productivity. This is unfortunately the case in much of sub-Saharan Africa.

3.2.1. Water erosion

Water erosion is a complex phenomenon that poses a particular threat to water and soil potential. It is defined as the detachment and transport of soil particles through the action of various agents, from their original location to the place of deposit.

The three stages of erosion are **detachment, transport** and **sedimentation**. Rainfall and run-off are at the origin of the detachment, transport and deposit of the soil particles torn away (Figure 7).

20 See also COLEACP Handbook on *Sustainable and Responsible Production*, Chapter 2.

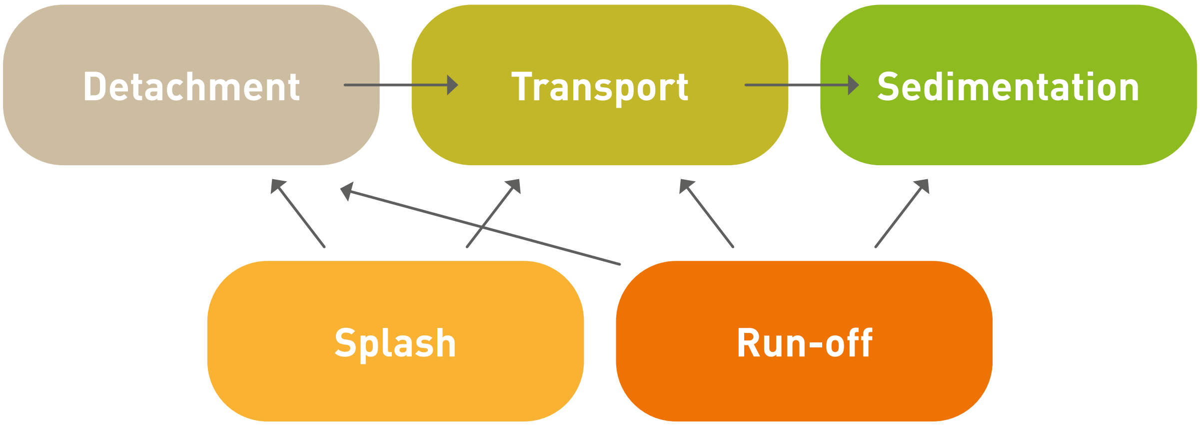


Figure 7 - Stages in water erosion

Stage 1: particle detachment

Wetting by raindrops is followed by four principal mechanisms that are responsible for disintegration and that lead to detachment of soil particles.

- **Break-up**: This corresponds to disintegration through compression of the air trapped during humectation. The intensity of the break up depends on the volume of air trapped (among other things), and therefore on the initial water content of the aggregates and their porosity.
- **Differential swelling**: This phenomenon occurs following the humectation and dessication of clays, resulting in cracks in the aggregates. The scale of this mechanism depends largely on the content and nature of the clay in the soil.
- **Physicochemical dispersion**: This corresponds to a weakening of the forces of attraction between colloidal particles during humectation. It depends on cation size and valence (in particular of sodium) linking the negative charges in the soil.
- **Mechanical disintegration under the impact of raindrops (detachment by splash)**: The impact of raindrops can fragment aggregates and, in particular, detach particles from their surfaces. The size and impact of the drops are important factors in this destruction and detachment process. This mechanism is generally combined with those described above, and requires rainfall with a degree of energy that varies depending on the soils concerned. The kinetic energy of the drops is not absorbed, but is transformed into a shearing force that results in detachment and splash. The kinetic energy of the drops that fall is generally used as a parameter for determining the erosive power of rainfall. In Africa, this kinetic energy can be two to six times higher than in temperate zones. This explains the importance of plant cover for the soil, which will act as a shock absorber for the raindrops (absorbing much of the energy): to reduce erosion by 50%, just 30% of litter cover is required, or 60% of a 50 cm canopy.

The combined action of detachment and displacement through rainsplash is probably the reason why this has often been seen as the sole process behind surface sealing and erosion. However, splash and structural degradation should not necessarily be grouped together; splash can, in certain cases, move aggregates without any disintegration occurring. The energy of a single raindrop coming into contact with the soil causes erosion by splashing or spraying that may move the particles detached by a dozen or so centimetres (micro-aggregates or elementary particles <100 mm). The soil mass detached may amount to several dozen tonnes per hectare per year.

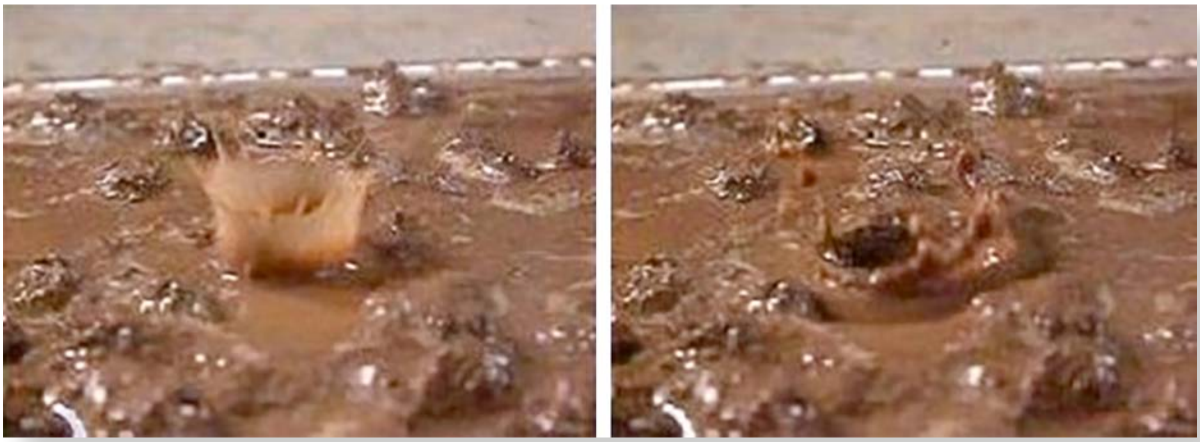


Figure 8 - Effect of raindrop splash on soil

Stage 2: particle transport

Transport is performed by rainwater, even where the gradient is slight. It is caused both by raindrops (splashing effect) and run-off on the soil surface. However, transport by splash effect is generally negligible except on steep slopes; the transport of detached soil particles is mostly attributable to **water run-off**. To limit transport, run-off must therefore be limited (slowed), for example by establishing grassed buffer strips.

Soil erosion occurs when rainwater cannot penetrate the soil and runs off a parcel of land, taking soil particles with it. Rejection of excess water by the soil occurs when the intensity of rainfall exceeds the soil surface infiltration rate (Hortonian run-off), or if the rain falls on a surface that is partially or totally saturated by groundwater (saturation-excess run-off). These two types of run-off generally occur in very different environments, although a combination of the two can sometimes be seen.

As the run-off increases, its speed and volume increase together with its capacity to create erosion. The critical run-off speed resulting in the transport of disintegrated particles is 5 m/s on sandy soils and 8 m/s on clay soils. Once run-off begins on a parcel of land, erosion can take various forms that combine over time and space, and can give rise to widespread erosion and/or concentrated erosion. At landscape level, water erosion translates into the formation of channels or ravines.

Stage 3: sedimentation (or particle deposit)

The agent responsible for sedimentation is run-off water. Particles taken from the soil are deposited between the place of origin and somewhere downstream, depending on:

- their size
- their density
- obstacles on the soil (vegetation slows run-off and acts as a filtration barrier, retaining the particles)
- the carrying capacity of the run-off.

Particles are deposited in the following order: sand, then fine sand, then silt. Clays and colloidal humus are generally transported to the mouth of the stream, where they are deposited following evaporation of the water or after flocculation.

3.2.2. Wind erosion

The phenomenon of wind erosion can occur anywhere with the soil conditions, climate or vegetation that favours its occurrence; that is, where:

- the soil is soft, dry, fine and crumbly
- the soil surface is relatively even and plant cover is absent or sparse
- the field is sufficiently large
- the wind is sufficiently strong to cause particles to move.

The effect of wind on the surface depends on the characteristics and condition of the upper level of the soil. The wind speed required to cause movement of the more sensitive particles therefore depends on the size and density of the detachable particles. The wind speed must consequently be 15 km/h at 30 cm above the soil to be able to dislodge soil particles of about 0.1 mm diameter. On a flat surface, particles are at a height sufficient to absorb a relatively strong force, but their light weight allows the wind to move them more easily.

The speed and extent of the erosion caused by the wind depends on the following factors.

2.2.2.1. Erodability of the soil

The wind can lift very fine soil particles high in the air and transport them over long distances (suspension). It can lift medium to fine particles over short distances and cause them to move in short, successive leaps and bounds that damage crops and disturb the soil still further (saltation). If the soil particles are too big for the wind to lift them, the wind dislodges them and causes them to roll over the soil surface. The abrasion caused by the movement of particles blown by the wind degrades stable aggregates on the soil surface, which further increases the erodability of the soil.

Semi-arid tropical areas are particularly sensitive. During the dry season, overgrazing can lead to the disappearance of a large proportion of plant cover, leaving large surfaces unprotected so that the structure then deteriorates. As with water erosion, the layer that is richest in nutrients is eroded, resulting in a decline in soil fertility.

In the Sahel, when crops begin to grow, violent winds accompanying storms and preceding the rain result in major sand flows on dry soils. During this phenomenon, young plants are damaged or covered by sand particles, leading to significant crop losses.

2.2.2.2. Roughness of the soil surface

When there is a wind, particles may dry more rapidly on the ridges of furrows created when the soil is tilled, which can result in further loose and dry soil being blown away. Over time, the furrows may fill up so that rough soils become flat as a result of abrasion. This leads to a smoother surface that is more vulnerable to wind erosion. Excessive tilling of the soil can contribute to breaking up the soil structure and thereby increasing erosion.

2.2.2.3. Climate

The force of the wind and the duration of windy periods have a direct effect on the extent of soil erosion. The levels of humidity are low on excessively drained soils and during periods of drought, which results in particles becoming detached and being blown away by the wind. It has been noted in Africa that wind erosion occurs where rainfall is less than 600 mm on bare soil, and when there are wind speeds in excess of 20 km/h or 6 m/s on dry soils. Wind erosion can also occur in humid climates when certain months of the year are particularly dry, and where the soil is prepared using farming techniques that break up the soil surface.

Figure 9 - Erosive force of wind in an unprotected field

In the absence of trees, shrubs and residues that form barriers to wind, the wind moves soil particles over long distances, increasing soil abrasion and erosion. As mounds and hilltops are usually exposed, these are the places that suffer the most, and the absence of permanent plant cover makes them highly vulnerable to wind erosion. Bare, dry and exposed soils are the most vulnerable.

3.3. INFLUENCES OF CULTIVATION PRACTICES ON SOIL QUALITY

3.3.1. Influence of cultivation practices on soil quality

Effects of ploughing on soils

Industrial/intensive agriculture, which uses machinery, requires farmers to create ever larger plots. This drives them to remove hedgerows and trees alongside fields. Added to deforestation, this reduces the number of roots giving structure to the soil and preventing erosion during heavy rains.

Ploughing is the most common tillage technique or cultivation method (Figure 36). The plough opens the soil to a certain depth[21] and turns it over so it is ready for sowing or planting. Ploughing, through tillage, erases the tyre marks and ruts caused by heavy harvest machinery. It also facilitates sowing using a lighter seed drill, and allows crop residues (such as straw), fertiliser and manure to be worked in deeply. Ploughing also destroys weeds.

Figure 10 - Ploughing: to halt the deterioration of soils, agricultural practices that weaken soils must be limited, such as frequent or deep ploughing
Source: P. Sylvie/IRD-CIRAD

21 Ploughing performed with animal-drawn equipment does not dig as deeply as ploughing done with a tractor, which is much more powerful. Working in manure or crop residues is more difficult, but with animal-drawn equipment there is far less effect on soil structure and there is less soil compaction than with a tractor.

Ploughing, a technique typical in industrial agriculture, is one of the main causes of **erosion**, especially if it fails to take into account the slope of the land, since it encourages water run-off and the dragging of sediment down the slope. In addition, ploughing can leave the soil bare for several months if a cover crop is not planted immediately (to cover the soil and capture the available nitrogen, preventing contamination of the water table). When the soil is bare, there are no roots to stabilise the soil, water is no longer retained and the erosion increases.

The technique of ploughing also leads to **soil compaction** (Gagnon, 2009). Soil particles are rearranged under the effect of external pressure resulting from the circulation of heavy machinery or the passage of ploughing tools through the soil. Repeated passages of tractors, heavy-axle loading and tillage under overly humid conditions increase the risks of compaction. A vicious circle can then emerge, where the work is done on increasingly compacted soils and where the crops have ever greater difficulty in developing. Compaction leads to a **reduction in porosity**, and therefore in the volume of air contained in the soil. The exchange of air between the soil and roots, and therefore also the work of microorganisms, becomes more difficult. In addition, the compaction of soils prevents water from quickly penetrating the soil during rains, which further encourages run-off and therefore erosion.

The **loss of soil biodiversity** is notable in intensively cultivated areas[22]. Weedkillers and insecticides kill earthworms, mites, etc., which contribute to the life of the soil. Ploughing is also harmful to boidiversity as the ploughed earth, exposed to the sun's rays, is 'burned'. Here, too, a vicious circle is established: if the soil's microbiology is absent it no longer oxygenates the soil and no longer consumes organic waste, so the soil is poorer in nutrients, which encourages the use of chemicals that kill soil fauna.

Cultivation without ploughing

Ploughing is avoidable and can be replaced by simplified cultivation techniques such as **strip till** (limited tillage on the seeding strips only), **ridge till** (on ridges), or **mulch till** (work on the surface only and without working in crop residues).

Another technique is direct seeding under cover, combined with effective crop rotation, to avoid ploughing. The subject of **no-plough cultivation** is topical due to the quest for greater economic efficiency on farms to optimise the energy expended and working time. Questions on this subject raised by producers often give rise to debates: what are the impacts on soil, the environment, the farm's economy, working time, etc.? The motivations for adopting no-plough techniques can vary, and the consequences from an agronomic, environmental and economic perspective differ from one farm to another, and even from one plot to another. There is no standard response: the decision-making process must be tailored to each situation.

It is advisable to remain very cautious. **Acidification**, which is a natural, inevitable and slow phenomenon, can increase in the surface horizon in a no-plough or direct seeding system. The addition of acid fertilisers without tillage concentrates acidity on the surface. Plants can accumulate alkalinity; ploughing can work them into the

22 See the work of Claude and Lydia Bourguignon who created Laboratoire Analyses Microbiologiques Sols (LAMS, www.lams-21.com), a soil analysis laboratory specialising in the ecological study of cultivation profiles to restore soil biodiversity.

soil when they die, restoring a balance. In simplified soil tillage, 100 to 300 kg of lime per hectare per year should therefore be added to restore a neutral pH. Lime is an inexpensive product that is essential to the correct functioning of soils.

The **simplification of tillage** often involves investment in one or more specialist no-plough tools. The move from ploughing to direct seeding also requires transition phases to reap the full benefits, and should be approached as part of an overall modification of the production system. The transition period is difficult for farmers, for several reasons:

- the soils need time to rebuild – positive returns are seen only after two or three years, and it takes about five years to achieve a truly virtuous system
- it is often difficult to stand firm when neighbours begin to notice the crops do not appear to be 'clean'
- there is no support to cover the risks, which the farmers bear alone.

Farmers who adopt this technique see reduced erosion of their soils, sometimes up to 90%, with erosion occurring only following very severe weather. The explanation for this lies in the soil structure. Without ploughing, soils regain good physicochemical properties due to increasing levels of organic matter and the formation of aggregates. The root networks and the increase in the number of tunnels created by earthworms (whose number is also growing) boost the infiltration capacity of run-off water. Animal and plant biodiversity increases and restructures the soils.

3.3.2. Effect of the single-crop farming

Why single-crop farming is problematic

Single-crop farming is the installation of the same crop (or a limited number of species) on the same plot for several consecutive seasons (as opposed to mixed cropping). Generally, production-oriented or industrial agriculture is single-crop. While it has the advantage of limiting competition for water, light and nutrients, it also depletes the soil through repeated withdrawals of the same elements and perpetuates parasitism specific to the crop (e.g. soil fungi, nematodes, soil insects). The consequences are the mass use of herbicides, the rejection of nitrates, the pollution of water and soil, etc. Single-crop practices are also extremely demanding of energy introduced into the production system from outside, creating a huge shortfall in energy, especially fossil fuel energy. To obtain one calorie of food, it is necessary to expend 10 to 25 times more energy to produce this level of nutrient (energy used as fuel for agricultural machinery, but also indirectly to produce fertilisers and the necessary plant protection products, not to mention the energy used for the management of food stocks during drying, ventilation, transport etc.).

Other outcomes of single-crop farming include water and wind erosion, increased risk of flooding, crop pest outbreaks, disappearance of game animals, and decline in natural pest predators. For example, single-crop farming of maize on ferrallitic soil in West Africa leads to a 28.5% drop in yield (Sogbedji *et al.*, 2006). Also for a depleted ferrallitic soil, IFDC (2002) reports a fall in maize yields of 10 to 75% without the addition of organic matter into the soil, and from 20 to 32% with the use of the legume mucuna intercrop over two years of production. This denotes the importance of constant soil restoration in continuous production systems.

Positive effects of combination cropping

Combination cropping involves planting two or more crops growing simultaneously on the same plot (Figure 37). This system has the disadvantage of causing interspecies competition for light, water and nutrients, and it contributes significantly to rapid depletion of the soil. However, combination cropping makes it possible obtain a multitude of agro-resources in a short time from the same area. It can give rise to intercropping if the species are planted in a specific order. When combined with leguminous plants, this can lead to an improvement in nitrogen availability.

Figure 11 - Mucuna pruriens, an important leguminous plant often used in combination cropping

Positive effects of crop rotation

Crop rotation is a basic agronomic principle. This system consists of establishing two or more crops in a given order, according to the seasons or years of cultivation. It is effective only if the succession of crop species is chosen well (see Table 9), because certain previous crops are unfavourable to the crop that follows[23]. For example, for green beans certain previous crops should be avoided while others are recommended. A rather long rotation is recommended, or alternatively a prolonged fallow, for plant health reasons, particularly to avoid seedlings damping-off due to *Rhizoctonia solani.* As plants have roots of different lengths, rotation achieves better use of soil by plant roots, allowing some to exploit deeper layers.

23 See also the technical itineraries and good practice guides published by COLEACP, available at https://eservices.coleacp.org/en/e-library.

Table 2: Suitable crop rotations for green beans

Previous crops:		
not recommended	unfavourable	recommended
Aubergine	Capsicum, celery, lettuce	Bissap (roselle)
Beans, peas	Carrot	Beetroot
Courgette, watermelon	Groundnut	Cabbage, turnip
Jaxatu (African eggplant)	Onion, garlic, shallot	Cassava
Lettuce		Cereals where residues are not worked in (maize, sorghum, millet)
Melon, cucumber		Strawberry
Okra		Sweet potato
Potato		

The cereal–legume rotation is the most beneficial because it introduces nitrogen-fixing leguminous plants, which enable the **symbiotic fixation of atmospheric nitrogen**. The availability of nitrogen to the subsequent crop increases after incorporation and decomposition of mulch from these leguminous plants (Ledgard and Giller, 1995). But most of the time, leguminous crop plants with edible seeds export 60 to 70% of the nitrogen biologically fixed to their pods and seeds, which is a huge loss to the soil. The nitrogen balance in such a system can be negative. It is therefore much more valuable to use non-consumable leguminous plant seeds such as mucuna and lablab, and to incorporate residual organic matter to increase the soil's nitrogen content and organic matter.

Figure 12 - Roots of leguminous plants colonised by nitrogen-fixing bacteria (when a nodule is cut it appears red, distinguishing it from female of gall nematodes)

A well developed crop rotation facilitates discontinuity in the cycle of pathogens specific to crops, such as soil fungi and nematodes. It also helps to combat weeds by breaking their reproductive cycle. Crop rotation also allows for greater control of crop pests, which are no longer able to find their host plant, and it optimises the use of nutritional resources.

3.4. THE CONSEQUENCES OF DEFORESTATION FOR SOILS

3.4.1. A major global phenomenon

Forests, which are home to 80% of terrestrial biodiversity, provide us with nourishment, protection and wood, and also play a key role in combating climate change. Plants are a major source of carbon: they hold 40% of the terrestrial carbon pool. Each year since 2013, the United Nations International Day of Forests (21 March) has marked the key role forests play for humans and for biodiversity.

Globally, at the beginning of the 19th century tropical forests covered some 16 million km^2; currently less than half of this remains. Deforestation involves the clearance of parcels of forest land following overexploitation of the forest, or in order to free up land for other uses. Each year, this leads to the disappearance of some 13 million hectares of forest around the world. Deforestation is expanding rapidly in sub-Saharan Africa due to the continuous destruction of forests.

Most forests around the world have provided a great service to humans. The forest covers, protects and conserves the soil; it provides energy (firewood, charcoal), lumber for construction, leaves, animals, fruits and roots, honey or sap for food or as medicines, and nutrients gleaned from the depths (agroforestry); it stores carbon and releases oxygen; it improves the local climate and has a positive impact on ambient humidity and rainfall patterns; and it purifies the air, removing pollutants. These are the ecosystem services rendered by forests; losing the forest means losing these precious services.

3.4.2. What are the causes of deforestation?

Some of the main causes of deforestation in tropical areas are as follows.

- **Agricultural expansion**: This may be subdivided into several types of activity that all lead to the conversion of forests: family subsistence agriculture, such as itinerant slash-and-burn agriculture; perennial or semi-perennial crops, be they family or agro-industrial; large scale farming.
- **Logging**: Lumber wood is all too often exploited in a destructive way in tropical regions (even if sustainability labels are becoming widespread among major forestry companies). According to Fleury (2000), tropical forests were exploited for their precious wood, then for lumber, and finally for paper pulp.
- **Production of charcoal or use as firewood**: Wood is often the only fuel available or accessible to populations to provide the energy necessary to cook food and process agricultural products. According to FAO (2005), 80–90% of wood felled in Africa and South-East Asia is used as fuel for the preparation of meals, or used for heating.

- **Expansion of infrastructure and mining**: The impact of the mining sector on forest cover can be direct: mining involves pollution and degradation of natural habitat through the elimination of substrate on surfaces ranging from less than a hectare to dozens of hectares, depending on the mineral extracted. This impact is irreversible in the absence of any rehabilitation efforts.

3.4.3. What are the consequences of deforestation?

The consequences of this deforestation are numerous.

- **Soil degradation**: Loss of organic matter, erosion and soil stripping. The role of trees is particularly important on slopes if soil is to be retained.
- **Loss of biodiversity**: The destruction of forests results in the disappearance of natural habitats for fauna and flora. The animal and plant species concerned are weakened and may even disappear if the resources available are not sufficient.
- **Climate change**: This is due to the release into the air of massive amounts of CO_2.
- **Natural disasters**: Through their roots, forests serve to conserve the soil, combat avalanches and landslides, stabilise sand dunes and protect coastal areas. The destruction of trees leads to catastrophic flooding as run-off is not being slowed by plants, leading to mud flows as soils are no longer held in place by roots.
- **Diminished water resources**: Deforestation has an impact on run-off. Forests make it possible to slow the movement of water: leaves and other organic matter found on the forest floor absorb water from heavy downpours and release it slowly and gradually to the soil below. The water resurfaces much later in springs that feed waterways. Trees thus make it possible to retain water and reduce erosion.
- **Increase in diseases**: Species that are natural antagonists to disease vectors (such as mosquitoes) have nowhere to shelter.

Impact of deforestation on soil

Deforestation has a number of direct and indirect effects on soils.

- **Reduced soil protection:** Forests protect soils against rain and wind as the density of forests provides natural protection against wind flows. Due to deforestation, soils are left without protection and become more fragile.
- **Reduced water saving:** By encouraging the infiltration of water due to their roots, and evapotranspiration through their leaves, trees increase soil water retention. Once deprived of their forest cover, hill slopes lose the ability to regulate water run-off, and the level of waterways and rivers fluctuates rapidly, often resulting in devastating flooding downstream. Deforestation leaves the soil bare and there is a noticeable increase in soil temperature, which reduces soil humidity. The vegetation then disappears due to a lack of water.

- **Loss of humus:** Rainwater run-off leads to the destruction of humus. Once deforestation has occurred, the forest litter is removed and the soil loses its nutrients.
- **Soil sensitivity to erosion:** Mass deforestation and logging on mountain slopes makes the soil particularly sensitive to water erosion (FAO, 1983). Deprived of their forest protection, bare soils are also exposed to violent winds, heat and heavy rains, so that the soil erodes rapidly. Erosion therefore adds to run-off, since water runs more easily along an eroded soil. But run-off also exacerbates erosion: the water running down takes the soil with it, which can have an abrasive effect on the ground experiencing the run-off.
- **Weakened soil structure**: The soil becomes sensitive to the phenomenon of compaction. It loses its water retention properties and can no longer shelter significant macrofauna (earthworms and termites) that provided it with nutrients and improved its physical structure.
- **Soil salinisation**: The deforestation of slopes and the conversion of forested areas for cash crops results in an increase in the levels of salt water in the plains and to the 'modern' salinisation of vast tracts of cultivated soil (e.g. San Joaquin Valley in California, USA).

Effect of global warming

Deforestation releases the carbon originally stored by trees into the atmosphere, exacerbating the greenhouse effect and contributing to global warming. An assessment by the FAO (2015b) shows that the destruction of forests at global level releases close to 2 billion tonnes of carbon into the atmosphere each year.

Forest clearing and desertification

The destruction of forests for agricultural production is a major cause of deforestation. When land is cleared for growing crops in humid and sub-humid areas, the trees must be cut to a stump or even totally removed. Mechanised clearance is the most destructive. Where only hand tools are available the clearance methods are, for the most part, more environmentally friendly.

Itinerant farmers operating in the same areas for many years (or centuries) are aware of ecological factors that determine whether a crop system is sustainable. Under traditional systems, trees are pruned so that they can actively regrow shortly afterwards. Provided the crops are not continued for more than two years, the natural vegetation regenerates rapidly, the soil is protected, the nutrient cycle restarts and aggressive weeds do not establish. Five years after a short cropping period, the forest canopy regrows.

When alternative land is not available for crops, the period for which crops are grown must be extended. This results in the growth of weeds, the trees are gradually destroyed and, when the land is abandoned, it takes a lot longer for the natural vegetation to regenerate.

Pressure for land sometimes leads families to look for land in forest areas that have not previously been used for agriculture (e.g. in Guinea and Senegal). In semi-arid areas, a larger surface area must be cultivated for a family's survival than in a humid area. Farmers are sometimes obliged to till in new areas (e.g. displaced persons and refugees), and in such circumstances they are more concerned about sufficient food production than about ensuring their methods are sustainable. As such itinerant farmers have no right to the land they occupy, they have few incentives to improve its future productivity.

Itinerant cultivation can degenerate into **slash-and-burn**, with significant damage to the soil. Annual burning of vegetation drastically reduces the return of organic matter to the soil, which loses all its advantages (fertility, better structure, water conservation, biodiversity), and the land becomes impoverished. In addition, the regrowth of vegetation after clearing for crops is far slower in semi-arid regions. Herbaceous weeds establish themselves rapidly and the recycling of nutrients may be negligible under such conditions. Where most tree stumps have been removed to permit ploughing, the re-establishment of plant cover is a far longer process (referred to as **desertification**).

Community wooded areas have also been impaired by the removal of firewood and tree trunks for intensified construction. It is difficult to establish individual titles for the use of land in areas that cannot be cultivated, but greater recognition of community rights is essential to encourage user associations to cooperate to ensure adequate management of such areas.

3.5. THE CONSEQUENCES OF OVERGRAZING

Animals are a major component in the food production system in arid, semi-arid and sub-humid regions. The value of **manures** has long been widely recognised in agricultural production. They are essential for sustainable agricultural production in most systems with a low or intermediate level of inputs. Manures are also essential as a factor in integrated nutrition management systems, even when high levels of inputs are employed. Cattle are also important as draught animals, and as a mark of status and wealth, in many areas of sub-Saharan Africa.

Population growth often leads to an increase in livestock. Pasture land can only support a limited number of head of cattle due to the quantity of plants produced and the availability of water. If the cattle population increases in an unrestricted way, the pressure on pasture areas results in a loss of edible plants and the dominance of shrub species, ultimately resulting in desertification.

As the cultivated surface area increases, the best soils are chosen for crops so the productivity of the remaining pasture land declines. Around water sources used as watering troughs, plant cover may be destroyed and the soil compacted by trampling, increasing the quantity of run-off water. This may help to keep water reservoirs full, but as little water can penetrate into the soil around watering areas, sudden flooding may occur, resulting in serious erosion.

Figure 13 - Effect on soil of a concentration of cattle at a water source
Source: Maliweb.net

Sustainable land management requires not only sustainable agricultural production systems, but also long-term animal production systems, these systems ideally being integrated (integrated agricultural production management).

In most sub-humid and semi-arid areas, much of the pasture land is burnt each year during the dry season to remove the old, tough vegetation and encourage young shoots and more nutritious grasses. This **burning** results in the loss of organic matter from the soil and therefore alters the sustainability of agricultural production. In addition, it exposes the ground to the erosive forces of wind during the dry season and of rain when the dry season comes to an end. The detrimental effects on the soil can be minimised by ensuring that burning is conducted early in the dry season – but this can only be an imperfect solution.

Pasture land is generally considered to be common property, and access is generally limited to members of a particular community. When the community becomes larger, the number of head of cattle using the pasture land increases, resulting in the land becoming degraded. Pressure to reduce the number of head of cattle has generally been ineffective due to the social and economic role of animal ownership.

3.6. SOIL SALINISATION

3.6.1. Defining soil salinisation

The salinity of a soil derives from the presence of major mineral solutes dissolved in water or in the soil. It is the measurement of total salts dissolved (Slama, 2004). Soil salinisation refers to the gradual increase in the concentration of hydrosoluble salts in the soil solution as a result of natural (primary salinisation) or anthropogenic (secondary salinisation) factors. The world is losing an average of 10 ha of cultivable land per minute, 3 ha of which is due to salinisation (Kovda, 1983). Saline soil covers large surfaces on all continents and under all climates (Table 3 presents some examples).

Table 3: Salinisation problems of primary and secondary origin

Region	Country*	Total surface area (Mha)	Cultivated surface area (Mha)	Salinised surface area (Mha)	Salinised surface area (%)
Africa	Ghana	22.8	4.5	0.8	3.5
	Kenya	56.9	4.5	8.2	14.4
	Nigeria	91.1	32.9	5.6	6.1
	Tanzania	84.4	4.0	2.0	2.3
Middle East	Egypt	99.5	3.3	9.1	9.1
	Iran	162.2	19.4	27.4	19.9
	Syria	18.4	5.2	0.5	2.7
	Tunisia	15.5	4.9	1.8	11.6

*Countries in the FAO network for integrated soil management for saline soil use.
Sources: FAOSTAT, 1997 (total surface area, cultivated surface area); Mashali et al., 2005 (salinised surface area)

Soil salinisation is one way in which soil productivity may decline without any loss of soil cover, a scenario very similar to that of soil pollution from chemical products. The soil becomes rich in soluble salts and, to a greater or lesser extent, overly salty (Servant, 1975). According to Cherbuy (1991), this is a process attributable to the migration of salts through the soil profile and their accumulation, through precipitation, deep in the soil. Soils with salinisation problems have an excessive concentration (electrical conductivity (EC) >10 deciSiemens per metre (dS/m) of water-soluble salts (saline soils), sodium absorbed in the clay–humus complex (sodic or alkaline soils), or both (alkaline saline soils). It is claimed that, for most plants, an EC >15 dS/m means that cultivation is no longer possible.

3.6.2. What are the factors that result in salinisation?

2.6.2.1. Main sources of salinization

Salinisation generally results from poorly drained irrigation in arid climates. Water stagnation in the upper layers of the soil due to inadequate drainage results in the accumulation of salts in the shallowest horizons, as their upwards movement due to the heavy evaporation that occurs in hot and dry climates greatly exceeds any permeation, and therefore leaching, of those salts.

These salts have many sources.

- **Irrigation water oversaturated in solutes**: this is the major source. Combined with defective drainage and/or high evaporation, it is likely to result in a concentration of salt in the soil so that it can no longer be cultivated. This process can be very rapid and may emerge within a year, a decade (as in the Inner Niger Delta in Mali), or several centuries (as with the Euphrates and Mesopotamia). This type of salinisation is the consequence of unsuitable farming practices or developments. The water table may rise by several dozen metres, as in Kouroumari in Mali (40 m in 20 to 30 years). Excessive salt content is one of the principal concerns with water used for irrigation. A high concentration of salt in water or in soils will have a negative impact on crop yields, degrade the soil and pollute underground water. The risk of salinisation depends on the salt level of the irrigation water, but even if the irrigation water is of good quality with little salt, it should be remembered that salts may nevertheless accumulate in the root zone following each irrigation, due to evaporation. Water with high salinity (EC >1.5–2.0 dS/m) and a large quantity of sodium (SAR >6)[24] must not be used for irrigation, or it will have an impact on yields (see Table 4). In general, water used for irrigation should have low to average salinity (an EC of 0.6 to a maximum of 3.0 dS/m).

Table 4: Level of restriction imposed on water use for irrigation

Parameter	Level of restriction imposed on water use		
	None	Low to moderate	High
Salinity (dS/m)	>0.7	0.7–3.0	>3.0
Total quantity of dissolved matter (mg/litre of water)	>450	450–2,000	>2,000

In certain areas where water is scarce, highly saline water may be used to supplement other sources. Good supervision and good management are therefore essential.

If a farmer applies 10,000 tonnes of irrigation water a year, per hectare of harvest, between 2 and 5 tonnes of salts will be added to this land each year. Unless these salts are rinsed, enormous quantities may accumulate over the years or decades.

24 SAR: sodium adsorption ratio [meq/l$^{1/2}$] as compared with that of calcium and magnesium.

- **Weathering of geological materials**: This may release the elements necessary for soluble salts to form. It can involve weathering of primary minerals rich in sodium, volcanic rocks, the products of hydrothermal phenomena rich in sulfur and chlorine, or even the dissolution of evaporites, which are ancient saline accumulations.
- **Sea water**: This is a key source of salt in coastal environments. Salinisation may be a constant phenomenon linked to the tides (marine salinisation) or even due to the presence of overly salty duckweed when low-lying areas are separated from the sea by alluvial deposits (lagoon salinisation, as in the case of Lake Retba in Senegal). These areas are highly sensitive to water management upstream. Great care must therefore be taken in coastal areas, where the infiltration of sea water poses a major risk for the salinity of irrigation water that is pumped from wells.
- **Changes to the hydrology of major rivers**: Through abstraction or regulation by dams, such changes can intensify the salinisation of underground waters and subsequently of the land. Soil degradation by salinisation has a greater impact on hydro-agricultural developments in arid or semi-arid areas.
- **Groundwater**: This may be of continental origin and saline due to its geological heritage, and can contaminate the soil as a result of upward capillary movement.
- **Certain farming practices**: Practices such as deforestation and inappropriate developments may lead to salinisation.

Figure 14 - Saline soil in a desert climate: the accumulation of salt in the upper layer of the soil is linked to the presence of a slightly salty water table less than 5 m below ground
Source: Alain Ruellan, AFES

2.6.2.2. Sodium salinisation

The presence of sodium (Na) poses a particular problem for irrigated soils. Sodium is one of the least desirable elements in irrigation water. This element comes from the weathering of rock and soil, sea water, treated water and irrigation system ingress. The principal problem with a large quantity of sodium is its effect on soil permeability and water penetration. The sodium replaces the calcium and magnesium absorbed on the clay particles and results in the dispersal of soil particles. The soil aggregates therefore crumble, when dry resulting in a hard and compact soil that is excessively impermeable to water. When irrigated with water with a high sodium content, the permeability of sandy soils may not deteriorate as quickly as with heavier soils; however, a potential problem exists. Sodium also contributes directly to the total salinity of water and can be toxic for sensitive crops such as carrots, beans and onions.

Sodium concentration in irrigation water is estimated using the **sodium adsorption ratio** (SAR). The SAR gives the quantity of excess sodium as compared with the calcium and magnesium cations, the latter generally being tolerated in relatively large quantities in irrigation water. The SAR is calculated using the following equation (sodium, calcium and magnesium are expressed in meq/litre):

$$RAS = \frac{Na^{+}}{\sqrt{(Ca^{2+} + Mg^{2+})/2}}$$

Water with an SAR >9 should not be used, even if the total salt content is relatively low. Continuous use of water with a high SAR leads to a breakdown of the soil structure. Water with an SAR between 0 and 6 can generally be used on any soil type where the accumulation of sodium is not a major problem. When the SAR is between 6 and 9, there is an increased risk of problems with soil permeability.

When irrigation water is saline, an even lower SAR value should be used. Problems caused by sodium are also linked to the total concentration of salts in the irrigation water. Consequently, irrigation water with salinity between 1.5 and 3.0 dS/m and with an SAR >4 must be used with care. Soil samples must be taken annually to avoid potential soil salinity problems.

3.6.3. What are the consequences of salinisation?

The accumulation of soluble salts (sodium salts in particular) on the soil surface and in the root zone has harmful effects on plants, resulting in a fall in yields or even soil sterilisation (Mermoud, 2001). Subsequent precipitation of minerals in soils not only alters their composition, but also leads to different evolutionary paths of the soil profiles, depending on the relative abundance of the major ions in the initial solution. These major ions are calcium (Ca^{2+}), magnesium (Mg_2^{+}), sodium (Na^{+}), potassium (K^{+}), chlorine (Cl^{-}), sulfate (SO_4^{2-}) and carbonates (HCO_3^{-}, CO_3^{2-}).

The greatest danger for the soil is water being present in an excessive quantity, resulting firstly in clogging, and secondly in **a rise in the underground water level.**

The soil acts as a sponge, drawing up water through capillarity in the root zone. On the surface, the water evaporates little by little and the salt is deposited in the root zone. Plant roots must then exert a suction force that is greater than that used by the soil to retain the water: this is the osmotic effect. Osmotic pressure in the soil solution prevents water from penetrating into the plant.

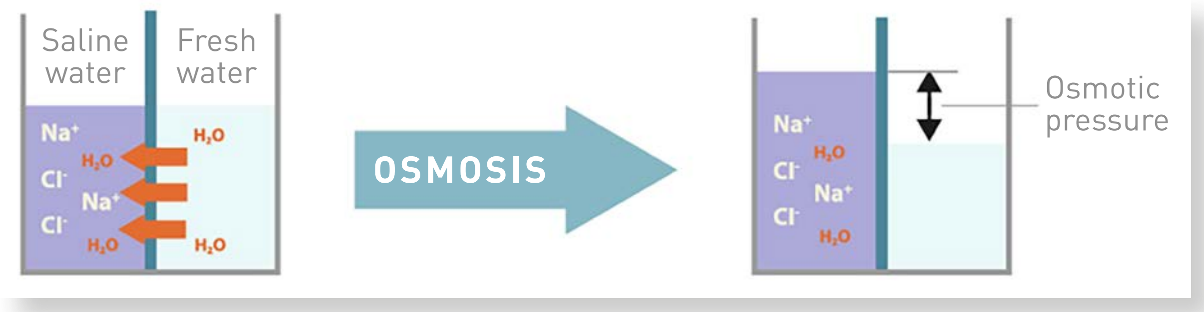


Figure 15 - Osmosis and osmotic pressure.

Due to the presence of these salts, certain elements such as chlorines, sodium or boron accumulate in the leaves and this may, in due course, cause metabolic damage (intoxication) that is often irreversible. Symptoms in crops caused by salt intoxication can be seen in yellowing, marginal chlorosis and even necroses of the terminal bud and leaf edges. Reductions in the surface or curling of leaves can also be seen. In extreme cases, the leaves will fall. Saline stress therefore leads to a reduction in crop yields.

Variations in pH can also occur in the wake of salinisation. For example, in certain soils, bicarbonate salts or sodium carbonates accumulate and the pH can rise to 10. Fertility is significantly reduced as many nutrients are insoluble at this pH.

Salinisation also reduces microbial activity in the soil which serves as the basis for the nitrification process. The organic products formed also change when soluble organic compounds increase and humic compounds decrease.

Vegetable and orchard crops are generally more sensitive than cereals to salt concentrations in the root zone.

3.6.4. Assessment of the risk of soil salinization

In addition to plant observations aside (the presence of salt-loving species), **soil ion analysis** methods must be used to assess soil salinity. The tolerance threshold for salt concentrations in the root zone is specific to each species.

Salt concentration is indicated by total dissolved solids (or the total quantity of dissolved matter) expressed in mg of salt per litre of water (mg/litre) or in g of salt per cubic metre of water (g/m^3) (mg/litre = g/m^3 = parts per million, ppm).

Overall salinity is generally determined by measuring the EC expressed in dS/m in a soil sample at a temperature of 25°C[25]. On average, 1 dS/m corresponds to 640 ppm of dissolved salts.

25 The EC may be expressed in millimhos per centimetre (mmhos/cm) or deciSiemens per metre (dS/m) or microSiemens per centimetre (1 dS/m = 1,000 µS/cm).

The following analysis method is used: 200 g of dry soil are sieved to 2 mm. Distilled water is gradually added to moisten the soil, which is mixed using a spatula to obtain a saturated paste. It is left for a minimum of 2 hours before being put into a device connected to a vacuum pump th*at filters the soil solution (extracted from the saturated paste). The filtration water is decanted and the EC can be measured (the values obtained must be corrected so that they are all aligned to the same temperature scale of 25°C).

Table 5: Tolerance of certain crops to soil salinity

Crops	Production level (%):				
	100	90	75	50	0
	Salinity of water extracted from saturated paste (EC in dS/m)				
Barley	6	8	10	13	20
Beans	1	1.5	2.3	3.6	6.3
Cabbages	1.8	2.8	4.4	7	12
Carrots	1	1.7	2.8	4.6	8.1
Citrus fruits	1.8	5.4	3.4	4.9	8
Garlic	1.2	1.8	2.8	4.3	7.4
Green onions	1.2	1.8	2.8	4.3	7.4
Maize	7	8	9	10	13
Melon	4.7	5.8	7.4	10	15
Peppers	1.5	2.2	3.3	5.1	8.6
Potatoes	1.5	2.2	3.3	5.1	8.6
Sorghum	7	8	9	10	13
Tomatoes	2.5	3.5	5	7.6	13
Watermelons/squashes	4.7	5.8	7.4	10	15

Source: Abrol *et al.* (1988)

The concentration of salt in irrigation water[26] can also be measured on the basis of the electric*al conductivity of irrigation water (ECi). The ratio between the salt concentration of the irrigation water (CEi) and its electrical conductivity (ECi) is approximately: Ci = 640 ECi.

26 As a reminder, there are five principal physicochemical criteria for assessing the quality of irrigation water:
- Salinity: total soluble salts content.
- Sodium: relative proportion of sodium cations (Na^{+}) as compared with other cations.
- Alkalinity and hardness: concentration of carbonate and bicarbonate anions in relation to the concentration of calcium (Ca^{2+}) and magnesium (Mg^{2-}).
- Concentration of toxic elements (to which the microbiological criteria for food health must be added).
- pH of water.

3.7. SOIL COMPACTION

Compacted soil is less productive, more sensitive to erosion and contributes less to the purifying and buffering functions of soils. Throughout the world, soils used by humans tend to compact, losing their porosity often over 10 to 50 cm depth. Compaction is most frequently caused by agricultural machinery, but overgrazing and over-frequentation of an environment by humans can contribute to this at local level.

3.7.1. Compaction due to trampling by cattle

While most small-scale producers do not use heavy agricultural machinery, in humid tropical countries the soil is particularly exposed to compaction through trampling by cattle.

Figure 84 - Land trampled by cattle
Source: Rémi Oriot

The speed with which water infiltrates is affected, run-off water increases, and plant roots are virtually unable to penetrate the soil and have difficulty in obtaining water. Soil compaction occurs particularly when it is humid and very rarely when it is dry. The longer the rainy season, the greater the risk. Trampling can result in the disappearance of plant cover and speed up soil erosion.

Sandy soils are less sensitive on the surface (Carrière, 1993). Overgrazed soils are characterised by bare surfaces and compacted horizons. Returning the land to cultivation may be problematic without sufficient tilling of the soil to give it depth (this is one of the keys to fertility).

It should also be noted that trampling by cattle is responsible for significant damage to waterways and reservoirs, notably by causing erosion of the banks, damage to river beds (pollution, expansion of the bed, silting, etc.), deterioration of the physicochemical quality of water, and a rise in temperature that may be detrimental to aquatic fauna. Consequently, as a result of soil compaction, strong run-off leads to sedimentation of the beds of waterways and to an increase in the turbidity (cloudiness) and nutrient load of the water.

3.7.2. Compaction caused by heavy machinery

The use of increasingly powerful and heavy machines results in greater soil compaction. This leads to compression of the coarse pores, preventing water and air from entering the soil. By driving on wet soil with heavy machines, the tyre profile presses into the soil and results in the crumbling and mixing of aggregates, and therefore destruction of the crumbly structure.

In the case of tilled soils, compaction (compression and asphyxia of the soil) is often accompanied by the appearance of a hardpan. Compression that results in a sharp fall in natural soil porosity is one of the most serious and common forms of soil degradation. Compaction of soils (particularly those rich in clays and/or silts) and their aggregates has a negative, direct and long-lasting impact on their biological activity and on their hydrological characteristics.

Excessive or inappropriate use of chemical fertilisers and certain soil amendments (but not manures, composts or other organic fertilisers, which improve soil quality) contributes to the destruction and compression of soils by breaking up aggregates and reducing biological activity. This is to the detriment of root penetration that normally, in conjunction with burrowing organisms, unclogs and builds up soils.

Figure 17 - On fragile, silty soils, repeated passage of heavy machinery is a factor in asphyxiation, degradation and potentially decline of the soil

3.8. SOIL POLLUTION

3.8.1. Pollution and contamination

A soil is deemed to be polluted if it has an abnormal concentration of chemical compounds that are potentially dangerous to the health of plants or animals.

Farm land may be polluted either before or during cultivation. This is why it is important to know the soil history over a number of years, particularly for the purpose of certain certifications that have made this a key requirement (e.g. GLOBALG.A.P. and organic farming).

Pollution may be defined as an unfavourable change to the natural environment as a by-product of human action and/or through the direct or indirect effect of human activities. These changes may affect humans directly, or through agricultural products, water and other biological products. Soil pollution involves the accumulation of toxic compounds: chemical products, salts, radioactive matter and pathogens, all of which have impacts on the growth of plants and the health of animals.

The soil has an interface with water and air, and therefore the notion of soil pollution is generally associated with contamination of one or more components of the ecosystem (air, water) or of living organisms in direct or indirect contact with the soil (particularly soil invertebrates and fungi). Beyond thresholds, which vary depending on the nature of the pollutant and soil, the pollution has an impact on the ecosystem.

The effects of soil pollution depend on the soil's structure and texture. Some soils have the ability to filter, absorb and recycle significant quantities of waste; in other soils certain toxic compounds are not retained, and are found in rivers and ground water. Sandy soils are prone to leaching, while thick clayey soils retain pollutants better. This means that all human activities involving soils must make allowance for the properties of the soil and the position of groundwater and waterways in the environment.

The soil may also be contaminated by pathogenic organisms that are harmful to humans (e.g. worms that are transmitted to humans and cause diseases) or to plants (e.g. pathogenic fungi or soil nematodes).

3.8.2. Origin and nature of soil pollutants

Soil pollution is generally due to an accumulation of **non-biodegradable** substances on and in the soil, such as metal trace elements including heavy metals [lead (Pb), cadmium (Cd), copper (Cu), arsenic (As), etc.]; or an accumulation (e.g. in organic matter) of **biodegradable** substances that degrade at a speed that exceeds the accumulation rate (organochlorine pesticides, dioxins, etc.). These substances can then be stored in the soil or leached by run-off water to neighbouring waterways or to the water table, or even evaporate into the atmosphere.

A large part of soil pollution can stem from fallout from atmospheric pollution, from thermal power plants, incinerators, foundries for lead and other non-ferrous metals, chemical industries, agriculture (particularly chemical fertilisers and pesticides), etc.

Soils can be contaminated by heavy metals (or other toxic metal trace elements), pesticide residues, hydrocarbons (diesel fuel, machine oil, mineral greases), fallout from atmospheric pollutants [e.g. dioxins, polychlorinated biphenyls (PCBs) and hazardous air pollutants (HAPs)[27]].

Certain farming practices (e.g. fertiliser application, irrigation, input of organic soil amendments) therefore introduce heavy metals into the soil. Products designed to improve the physicochemical properties of soil are often richer in heavy metals (Pb, Cd) than the soil itself, for example, **fertilisers, slurries, composts** and **water purification plant slurries** (and even copper from the application of Bordeaux mixture to combat blight). These inputs cannot be biodegraded or assimilated rapidly and therefore remain in the soil for a long time. Checks have shown high content of metal trace elements in manure: 0.7 mg/kg dry matter (DM) for Cd, for Zn and for Pb. Some small-scale farmers (e.g. in Benin, Cameroon and Democratic Republic of the Congo) use ash from household waste that they have burnt: this ash is generally very rich in heavy metals due to the batteries, cardboard boxes, plastics etc., that it contains and that are released when incinerated[28].

Waste from chemical factories is particularly rich in toxic elements (Naitormbaide, 2007).

Figure 18 - Landfill sites for household and industrial waste are sometimes returned to cultivation due to demographic pressure for land

The sources of pollution can therefore be classified as **natural** or **anthropogenic** (originating in human activity).

27 See definitions in the following pages.

28 Sorting before incineration can reduce the risk significantly: plastic is the principal source of cadmium (Cd) in household waste. Likewise, sorting glass results in a significant fall in arsenic (As), chrome (Cr), manganese (Mn) and lead (Pb).

Natural sources of soil pollution

Natural sources are less frequent and have more or less negligible consequences. There are, however, soils that are naturally polluted (soils rich in heavy metals or hydrocarbons) due to the following phenomena:

- volcanic action – a volcanic eruption releases large quantities of carbon dioxide and sulfur, but also heavy metals; every year volcanoes release into the atmosphere on average 800 to 1,400 t cadmium, 18,800 to 27,000 t copper, 3,200 to 4,200 t lead, and 1,000 t mercury
- meteorite falls (anecdotal)
- weathering of parent rock rich in elements that are progressively released and absorbed by roots that explore the soil and subsoil
- acid rain
- forest fires
- soil erosion, which releases elements that accumulate in shallows, often in areas reserved for vegetable growth in urban (or semi-urban) environments.

Anthropogenic sources of soil pollution

Anthropogenic causes are the most severe, as humans introduce into the soil enormous quantities of biodegradable natural products that exceed the assimilative capacity of the soil; synthesised products with a long half-life; and products that are not biodegradable. Human activities are therefore the most polluting, starting with **agriculture**.

The anthropogenic causes of soil pollution come from a range of human activities:

- Industrial plants (energy generation, metal working, chemical industries, etc.) can result in pollution of a site in the event of a leak, accident or even abandonment of a factory.
- The spreading of plant protection products and waste from livestock buildings and farms are also the origin of much soil pollution (in particular by nitrogen and phosphates) that will, in turn, also contaminate run-off water and subsequently waterways. Sources also include irrigation with polluted water, fertiliser application with household waste composts, etc.
- The actions of local authorities may also be the source of soil pollution, for example in the management of waste and water treatment plants.
- Geographically distant events can produce soil pollution, whether natural (e.g. ash from a volcano following a strong eruption) or technological (e.g. radioactive fallout).
- Urban activities (transport, management and processing of waste) also generate pollution.

The soil may be polluted in many ways:

- **Infiltration from landfill**: Household waste is a real problem for soils, particularly in towns where the rate at which it accumulates exceeds the soil's biodegradability capacity. Furthermore, most of this waste has low biodegradability (such as plastic). In addition, detergents, solvents and other chemical compounds end up in river water and/or lakes, where they contribute to eutrophication. It should also be noted that landfill contributes significantly to groundwater pollution.
- **Discharge of industrial waste**: Industrial discharges, in particular of heavy metals, are most toxic for the soil. Although some metals, such as zinc and copper, are necessary for plant growth, they are only beneficial in in low doses, while their presence in higher doses jeopardises soil fertility. Other heavy metals are toxic even in low quantities. This is the case with lead, mercury and cadmium, which cause plant phytotoxicity and pollute underground water, treatment of which is extremely costly. The soil pollution caused by discarding of pesticide packaging in fields should also be noted.
- Percolation of contaminated water.
- Leaks from underground storage reservoirs.
- Excessive application of pesticides, herbicides or fertilisers (e.g. some phosphate fertilisers contain cadmium).
- Incorporation into the soil of solid waste (e.g. the burial of chemical waste and unsorted household waste).

Figure 19 - Negligent dumping of hydrocarbons

Nature of the different types of soil pollutants

The substances present in the soil are extremely numerous; the principal pollutants are listed here:

- **Metal trace elements**: The concept of metal trace elements is tending to replace that of heavy metals, which was poorly defined since it encompassed not only toxic metals that were genuinely heavy, but also others (metalloids) that were less so. The family of metal trace elements includes arsenic (As), cadmium (Cd), cobalt (Co), copper (Cu), chromium (Cr), mercury (Hg), nickel (Ni), lead (Pb) and zinc (Zn). All metal trace elements are toxic, or toxic above a certain threshold. Their environmental concentrations (in water, air, soil, organisms) result from anthropogenic inputs (industry, transport) and natural inputs (volcanic activity, weathering of primary minerals). In agriculture, heavy metals mainly derive from spreading of water purification plant slurries and composts from household wastes.
- **PCBs (polychlorinated biphenyls)**: Very stable in the presence of heat, they only decompose at temperatures in excess of 1,000°C. Their chemical inertia means that they are not very sensitive to acids, acids, alkalis and oxidants. They are toxic, ecotoxic and reprotoxic (even at low doses, since they are endocrine disruptors). They are ubiquitous and persistent pollutants, with a half-life of 94 days to 2,700 years, depending on the molecules.
- **Dioxins**: These make up a group of chemically related compounds which are organic pollutants that remain in the environment. Dioxins are present in the environment throughout the world and accumulate in the food chain, primarily in animal greases. They are highly toxic and can lead to problems with procreation and development, and can damage the immune system, interfere with the hormonal system and cause cancers.
- **PAHs (polycyclic aromatic hydrocarbons)**: These are hydrocarbons that have leaked from the tanks in which they were stored: oil, various fuels, tars, aromatic hydrocarbons, paraffinic and olefinic hydrocarbons. PAHs are molecules in a sub-family of aromatic hydrocarbons. They have been studied in depth as they are compounds present in all environmental media and have been shown to be highly toxic. They have been recognised as having a carcinogenic, mutagenic and reprotoxic effect. In 2003 they were added to the products covered by the Stockholm Convention on Persistent Organic Pollutants and classified as products of great concern for health.

Other pollutants include:

- various solvents used in industry
- waste oils (e.g. used machine oil)
- pesticides (plant protection products)
- plastic materials buried in or discarded on the soil (bags, packaging, etc.)
- residues from paints, coatings
- asbestos residues.

The evolution of pollutants in soils

In general, whether pollutants come into being in soils will depend on the **physicochemical properties** of the substances [biodegradability, sensitivity to hydrolysis, solubility, affinity to fats, pKa, octanol–water partition coefficient (K_{ow})] and a certain number of joint behaviours between pollutant molecules and soil characteristics (including clay and organic matter content).

Metal trace elements, which are not particularly biodegradable, will accumulate in soils, with long-term consequences for the different soil functions.

- Soil microorganisms are the first living organisms to be affected by metal trace element contamination, seen in slowing of their activities and decline in their diversity and interactions.
- An increase in toxic element levels in soils results in increased uptake of these elements by the cultivated plants. The soil can then no longer produce food of sufficient quality to meet public health requirements.
- If metal trace element concentrations become too high, the fertility of the soil may be compromised due to the toxicity of these elements to plants, fauna and soil microfauna.
- Regarding seepage and run-off water, soils play the role of a purification filter, associated with its capacity to fix metal trace elements and accumulate them. Unfortunately this accumulation capacity is not permanent or unlimited. The release of metal trace elements and their transport by seepage or run-off waters can result in degradation of aquatic environments and diminish the quality of water, which may become unfit for consumption without prior treatment.

Certain **biodegradable** pollutants (e.g. most pesticides) are destroyed more or less rapidly by soil microbes. The soil is an ecosystem that (thanks to the microorganisms present) has a very high capacity to detoxify.

The degradation process for the active component ultimately results in mineral molecules such as H_2O, CO_2 and NH_3, being obtained. Degradation is carried out primarily by the biological organisms of soil microflora (bacteria, actinomycetes, fungi, algae, yeasts), the actions of which take place primarily in the first few centimetres of the soil. There are also physical and chemical degradation processes such as photodecomposition. These actions contribute to reducing the quantity of active matter in the soil and therefore to reducing the risks of pollution.

Pollutants that have not degraded, or have barely degraded, can accumulate in soil organisms and plants. Certain plants have remarkable affinities for certain pollutants: for example, lettuces and celery absorb more cadmium (Cd) than do cereals. It should be noted that the soil's ability to biodegrade pollutants depends on certain characteristics of the soil solution, and in particular its pH.

Physical, chemical, biological or bacteriological transformation of a pollutant may result in harmless metabolites – or, in contrast, they may result in metabolites that are more toxic than the initial product (e.g. AMPA [aminomethylphosphonic acid], a metabolite in Roundup®).

Highly soluble pollutants (e.g. certain pesticides) may be drawn down rapidly to the deep layers of the soil and pollute groundwater in the long term. But certain very polar and sometimes insoluble pollutants (hydrocarbons) can also rapidly reach water tables. By contrast, some pollutants can rise to the surface as a result of capillary movements linked to evaporation or evapotranspiration. If their vapour tension permits, they will be volatilised. In general, whether a substance becomes a pollutant will be determined by its **mobility in the soil**.

For the most part, pollutants are absorbed, with varying degrees of permanence, on soil particles, particularly on colloids. Finally, certain pollutants are not dissolved and are fixed definitively in the solid phase of the soils. There are therefore phenomena where substances accumulate in certain parts of the soil. This is the case with pesticides[29]. As soon as the pesticide is emitted (sprayed), the deposit that is actually obtained is far less than the theoretical deposit, due to the phenomena of by-products, interception by plants and volatilisation. In addition, the concentration of a pesticide (e.g. a herbicide) in the soil will not remain constant. Over time, the pesticide will:

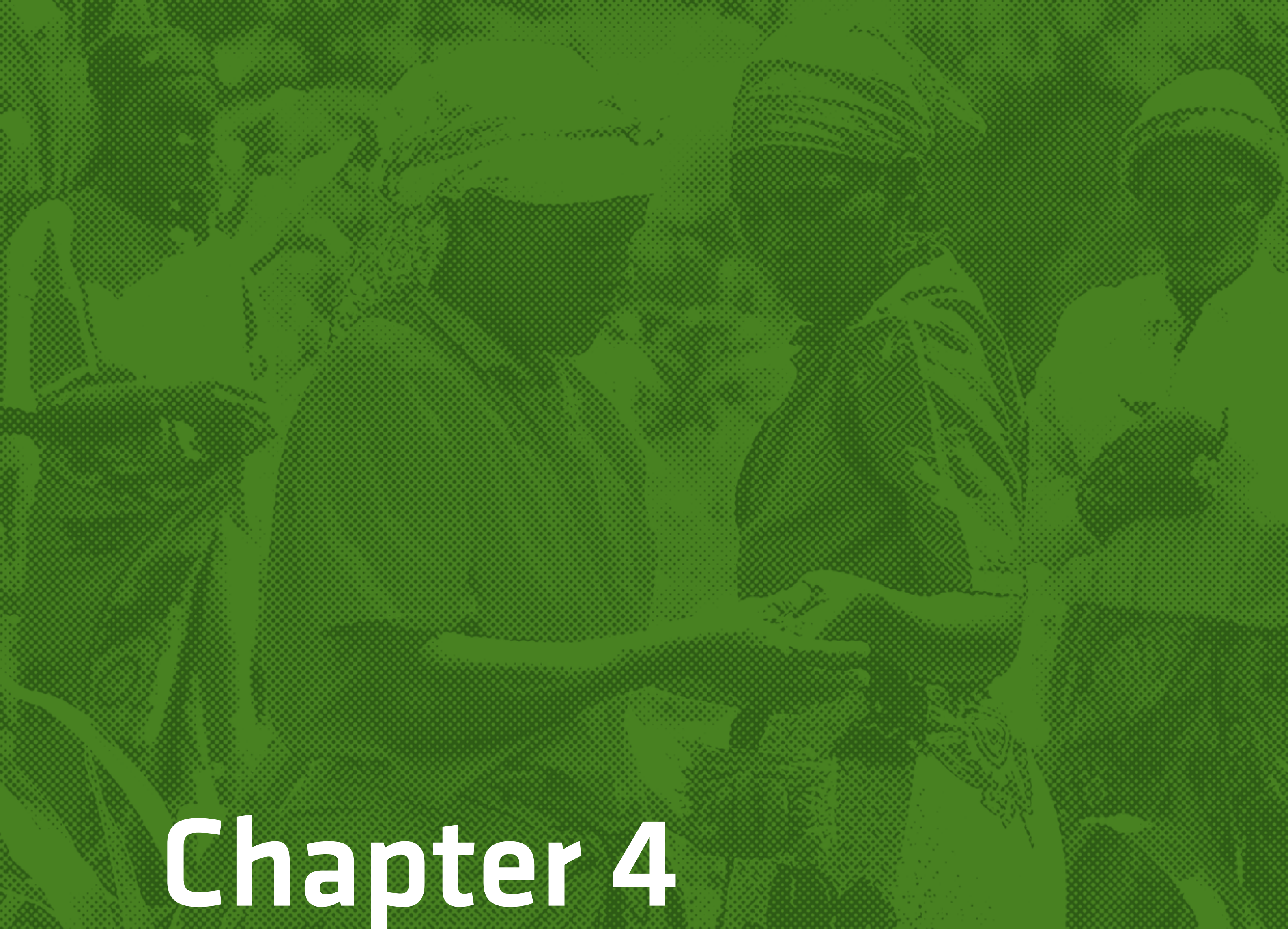
- attach to organic matter (more or less irreversible adsorption)
- transform (degradation and/or metabolism by plants and soil microbes)
- move (leaching downwards, lateral transport along the hardpan)
- desorb from the soil and gradually volatilise into the atmosphere.

This attraction between the pesticide and soil colloids is influenced by the properties of the pesticide (solubility, pKa, K_{ow}) and by the soil composition (percentage of organic matter, CEC, absorption capacity of the soil), its pH, concentration and availability in water. Temperature also plays an important role in adsorption. The phenomena of adsorption/desorption greatly affect what becomes of pesticides in the environment. Thanks to adsorption, they are no longer **bio-available**; are less active and less degraded by microorganisms; and are taken down into the soil to water tables more slowly. The residual concentration in the aqueous phase of the soil will determine efficacy or otherwise (bio-availability) and how long the action will persist, and will explain any effect on subsequent crops (phytotoxicity). Absorption by soil constituents, due to its impact on the concentration of a pesticide in the soil solution in the hours that follow its application, play an important role in its bio-availability.

The transport of the pesticide to the water table depends on its physicochemical properties, soil texture (micropores), soil structure (macropores), the biological properties of the soil (microbial biomass) and the climatic conditions (intensity and frequency of rainfall).

29 See COLEACP Handbook, *Sustainable production practices*, Chapters 2 and 4.

Figure 20 - Evolution and movement of pesticides in a soil profile – the knife indicates the level of the hardpan
Source: B. Schiffers



Chapter 4

Preserving and restoring soil fertility

4.1. Preserving soil quality and fertility 164

4.2. Restoring soil fertility 184

LEARNING OUTCOMES

After reading this chapter, you will:

- understand the basic principles of preventing soil degradation
- be aware of techniques to combat soil erosion by water and wind
- explain the role and importance of liming and the various soil improvers for preserving soil quality
- understand how to avoid the salinisation, compaction and pollution of soils
- be aware of the techniques for restoring soil fertility: mulching, combination crops, adding organic matter (compost, manure, liquid manure), fallowing
- understand the merits of some soil decontamination techniques using bioremediation.

4.1. PRESERVING SOIL QUALITY AND FERTILITY

4.1.1. Preventing soil degradation

Currently, 33% of land worldwide is moderately or seriously degraded due to erosion, salinisation, compaction, acidification and the chemical pollution of soil. The current level of soil degradation threatens the ability of future generations to meet their most basic needs. However, awareness is increasing about the necessity for a general reform of benchmark agricultural practices. 'Agro-environmental' measures (within the framework of agricultural policy in Europe) consist of assistance to farmers in order to, among other things, encourage soil protection actions. In 2002 the Convention on Biological Diversity established an International Initiative for the Conservation and Sustainable Use of Soil Biodiversity. Various countries (Australia, Brazil, Canada, Japan, USA and some developing countries) have created soil observation policies (inventorying and mapping hazards, status reports, maps of risks and dangers) and soil protection policies.

In many countries, particularly in tropical regions, intensive production systems with widespread mechanisation, implemented in order to obtain high agricultural yields, induce soil depletion. But soil is fragile, particularly tropical soil (which is often deficient in organic matter), and must be managed with care, both to prevent erosion by water and wind and to maintain its physical properties (e.g. avoid loss of structure or compaction), chemical properties (e.g. avoid salinisation or acidification) and biological properties (e.g. avoid reducing biomass and biodiversity), all of which are essential for optimum plant productivity in a given socio-economic context.

In order to effectively prevent the degradation of soil fertility, it is necessary to analyse, as closely as possible to the land, the risks caused by the nature of the soil and its organic matter content, cultivation practices (particularly soil tillage and fertiliser application), topography (particularly gradient), climate (particularly rainfall pattern), and type of crops planted (particularly soil cover). Respecting a certain number of **basic principles** will considerably reduce or slow the risk of degradation of soil fertility.

- **Reduce soil tillage** to the bare minimum and opt for the approaches adopted by conservation agriculture: 'eco-friendly ploughing' and alternative techniques such as 'scratching' the soil (at a depth of 5 to 10 cm), sowing directly in plant cover (the next crop is sown directly without prior destruction of plant cover) and strip-till (soil tillage only on the line of seeds, without disturbing inter-row areas). Otherwise, adapt tillage to the topography (e.g. do not plough the soil in the direction of the slope) or the depth of the soil.
- **Introduce plant cover** to protect the soil from heat, erosion, evaporation and nutrient leakage caused by rain. This will also prevent soil compaction caused by heavy rains (surface sealing). Plant cover will suffocate weeds, limiting the need to use herbicides that are harmful to the biology of the soil. Increasing the organic matter content of the soil increases its ability to store water.
- **Adopt integrated soil fertility management** (ISFM) by always combining inputs of fertiliser with inputs of organic matter. This will prevent acidification of the soils and enhance the fertilisers applied.
- **Improve the soil** by providing it with the nutrients (organic matter, lime, etc.) that will enable it to maintain a good structure on the one hand, and to naturally optimise its biological activity on the other. Soil improver feeds the soil, while fertilisers feed the plants.
- **Use irrigation sparingly**: avoid uncontrolled water inputs, and ensure good drainage to avoid the accumulation of salts in the upper layer of the soil.
- **Avoid polluting the soil** with toxic compounds such as pesticides, heavy metals present in some fertilisers or nutrients, hydrocarbons, household waste, etc. **Respect the integrity of the soil.**

4.1.2. Combating erosion

Soil erosion is one of the most crucial problems faced by agriculture today. This concern has led to the testing and development of techniques to combat erosion by water and wind.

4.1.2.1. Combating water erosion

We need to know the causes of this type of erosion, the evolution of the process and the links between erosion and soil condition, to choose improvement measures. Measures to combat soil erosion are always based on the following principles:

- reduce the strength of impact from raindrops – protect the soil against the direct force of rain
- improve soil stability (or resistance) – the degree to which the soil maintains its structure despite the impact of rain
- reduce the quantity of water leading to run-off, which enables better infiltration of water into the soil
- reduce the speed of the water and control the discharge of run-off water
- reduce compaction of the soil – for example, wheel tracks that concentrate water will accentuate run-off; low-pressure tyres compact and smooth the surface less and thus reduce the formation of furrows.

The presence of a crop that covers the soil well is an effective way to combat erosion: it reduces the impact of raindrops when they strike the soil; reduces the speed of run-off water; and increases the stability of the soil, its permeability and consequently the ability of water to infiltrate the soil.

Focus on the techniques of defense and soil restoration

A watershed is an area that drains water towards the same watercourse. In order to prevent and solve soil erosion problems and mudslides, action must be taken on the entire watershed or sub-watershed, as mudslides occurring downstream are caused by run-off water on the entire upstream area. The aim is therefore to first replant the area upstream of the watersheds, stabilise the ravines, restore the productivity of the land and protect dams from silting, before considering development upstream with terraces or other heavy techniques.

Figure 1 - Defence and restoration of sloping land on the watershed

Develop steep slopes

Over the centuries, farmers have tested a whole series of techniques to combat soil erosion caused by water, either with installations (stepped terraces or stone wall terraces, strip cropping, stone contour lines, ridges, cut-off ditches, banks, etc.), or by improving and thickening the plant cover (restoring grassland, associated cropping, etc.). All these techniques are aimed at slowing down water run-off along the slope.

Stepped terraces

These are the best known and most frequently used by farmers, but also the most complicated and expensive installations to implement. They are constructions that manage to break up the slope. These terraces take their name from the shape they give to the slope when it is fully developed: successions of terraces take the shape of a staircase or steps. The terraces cling on to the slope and must adapt to its gradient: when the gradient increases, the terraces are narrower and the retaining wall (or embankment) becomes higher.

Figure 2 - Stepped terraces supported by embankments

Strip cropping

Strip cropping is a less restrictive system than terracing on a hillside. This method consists of creating strips of a certain crop, such as maize, which does not cover the soil well, alternating with strips of denser vegetation such as small cereals, grass or leguminous plants. A large proportion of the soil is carried away by the water, is leached then and trapped by the thicker strip of vegetation which pushes below it. The original vegetation is kept in the places where the risk of erosion is the highest, and the strips are cleared alternately. In this way, strips that are well protected against erosion alternate with others that are less well protected.

Stone contour lines

These consist of three rows of stones arranged in a contour so that they reinforce each other. The stone contour lines slow the run-off, spreading it in layers so that it infiltrates into the soil in less than an hour, thus leading to the successive sedimentation of sand, aggregates, then fine particles of humus, which will form a sedimentation crust. Only the excess water runs over the first level of stones. Most of it will infiltrate into the soil, causing the fine particles and plant debris to be deposited. This can be a factor in soil fertiliser application.

This technique consists of removing stones from the plot and grouping them together in order to form a small row (two to three levels) aligned according to the contour lines. The spacing between two lines is reduced when the gradient of the plot of land increases. Sandstones and limestones are well suited to this type of construction. The dimensions of these lines are generally: base 0.4–0.8 m; height 0.3–0.5 m; length up to 40 m or more.

These stone lines are sensitive to heavy storms, which can dismantle them and cause them to collapse. Maintenance work thus depends on climatic variations and the solidity of the construction.

Figure 3 - Stone contour lines

- Advantages of this technique are that the products of stone removal can be reused; it is easy to set up; construction may be flexible and gradual; the technique has been used for centuries, is widespread and can be integrated by local populations; and it uses natural biological materials.
- Drawbacks of the technique include that it requires stones to be available close by; there may be insufficient infiltration when a slope is maintained; it must follow the contour lines and must cover the whole slope; and it is a vulnerable construction in areas frequently affected by storms.

Ridges

The ridging system was developed in East and West Africa. It makes it possible to increase water infiltration while reducing the run-off speed, and a reduced quantity of soil is therefore removed. There are different types of ridging: simple ridging and tied ridging. Ridges are traditionally made using a plough pulled by two animals. They are made following the contour lines in order to save on animal labour. On vegetable plots, soil tillage is carried out exclusively by hand (using a hoe). The ridges are constructed in order to lead the water from pit to pit. These ridges require daily maintenance, as they are sensitive to heavy storms and flooding, and to weeding for vegetable plots – the roots of weeds help to maintain the soil particles, when they are removed the soil becomes more sensitive to run-off.

Simple ridges are small rows of earth between 0.2 and 0.4 m high, installed according to the contour lines. Their width at the base can vary, and can sometimes reach 0.9 m. They are used on gentle slopes (2–3%).

For **tied ridging**, instead of following the contour lines, the ridges are connected by transverse or crosspiece dykes to form small pits of 2 to 10 m² surrounded by ridges of earth. The ridges can also be strengthened with stones when the plot is located on the bed of a wadi. Tied ridging is a tried and tested system combined with animal traction in developing countries such as Burkina Faso and Zambia. It adds roughness to the soil, which facilitates infiltration and slows run-off. This type of installation in the form of ridges enables the infiltration of the maximum amount of water, making it possible to grow many species. Species requiring large amounts of water are grown in pits, those that are more resistant to drought are sown on the ridges.

Advantages of this technique are that it increases and stabilises yield per unit surface area farmed; and it concentrates water in longitudinal, rectangular and diamond-shaped pits, which encourages infiltration and the storage of water in the soil. Two crops can be grown in the bottom of the pits and on the ridges, depending on the water requirements of the plants.

Drawbacks of the technique include the possibility of encouraging gullying if the ridges are not set up strictly according to the contour lines; strong sensitivity to excess water caused by storms or flooding; and difficulty in using it on slopes with a gradient over 12%.

Figure 4 - Installation of simple ridges in a vegetable crop pit

Creating grass strips

Grass strips around 20 m wide can be installed on slopes to encourage infiltration.

Figure 5 - Grass strips to combat soil erosion

Restoring grassland

The restoration of grassland is without doubt one of the most effective ways of reducing soil erosion. When grassland is located on slopes, it limits erosion and buffers run-off coming from upstream. When it is located at the bottom of a valley, it traps sediment and prevents it from being transported towards rivers. In the latter case, it also makes it possible to buffer watercourse flooding, playing a temporary retention role.

As far as possible, it is better to till the plots at a perpendicular angle to the slope. This makes it possible to reduce the speed of run-off water and the risk of gullying and mudslides. It is possible to plough the plot parallel to the contour lines up to a gradient of around 12–13%; beyond this point it is too risky to turn the tractor around. In addition, farmers generally till their plots along the longest axis, as this means they have to turn the tractor around less often and saves time. The plot must be approximately aligned with the contour lines for this technique. Cultivation following the contour lines is a conservation technique that involves ploughing and planting crops at a right angle with respect to the slope, following the contour lines of the land. By doing this, the roughness of the soil due to clods and small hollows is positioned perpendicular to the slope so that the water table that can run off is slowed as much as possible.

Figure 6 - Ploughing according to contour lines in Brazil (Source: FAO)

Before starting ploughing, a number of topographical measurements must be carried out using permanent orientation points. It is therefore preferable to dig furrows at an angle of about 1%, in order to collect the run-off water and discharge it using a drainage channel. The furrow must not be more than 100 m long to prevent flooding and reduce the speed of the flow. Drainage channels can be used, provided they are protected by plant cover. The furrows must be as horizontal as possible otherwise there may be disastrous consequences: water can accumulate at a slightly lower point and damage the furrow, as well as the furrows located lower down.

Earth bunds constructed at regular intervals in the furrows make it possible to control the water speed. This system is known as tied ridging. If the rains are not too heavy, all the water will infiltrate into the soil. This method is effective in dry areas.

It is a simple and effective method that can be combined with the construction of terraces and strip farming in order to increase its effectiveness.

Figure 7 - Tied ridging (Source: FAO)

4.1.2.2. Combating wind erosion

Combating erosion by wind takes place at two levels:

- **Increasing the soil's cohesion** faced with this stress
- **Reducing the wind speed** at the soil surface.

Increasing the material's cohesion

Adding organic matter to the horizontal surfaces of the soil improves its structure. In the places where the crop is watered, supplementary irrigation can be an effective and profitable method to reduce wind erosion problems. It is sufficient to irrigate the soil before the normal rainy season in order to enable ploughing under good conditions and installation of plant cover before the tornados that generally cause damage at the start of the rainy season.

Increasing the surface roughness of the soil

One cultivation technique is to leave large **mounds or ridges** perpendicular to the dominant wind direction at the soil surface. These ridges must not be higher than 40 cm, otherwise the wind will blow away the tops of the ridges and accelerate erosion.

Another very effective method is to leave **crop residues** in the field. For example, in Burkina Faso, when millet and sorghum stalks are cut at 1 m and left vertical to the surface of the soil, they trap a large volume of dust as well as leaves from trees that are blown by winds in the tornado season.

Installing windbreaks

In areas subject to high winds, but from a regular direction, the installation of **hedging plants** and **windbreaks** are well known methods. Their role is twofold: reducing the wind speed reduces both evaporation and erosion by wind. A windbreak makes it possible to reduce the wind speed by 20%. Its effectiveness extends to 10 to 12 times the height of the windbreak upstream and downstream. However, this protection depends on the permeability of the windbreak: low permeability leads to a greater reduction in speed, but it protects a smaller width. According to Heusch (1988), if the speed is reduced too much (the plantation is too dense), the temperature rises and the plants are scorched along the windbreak.

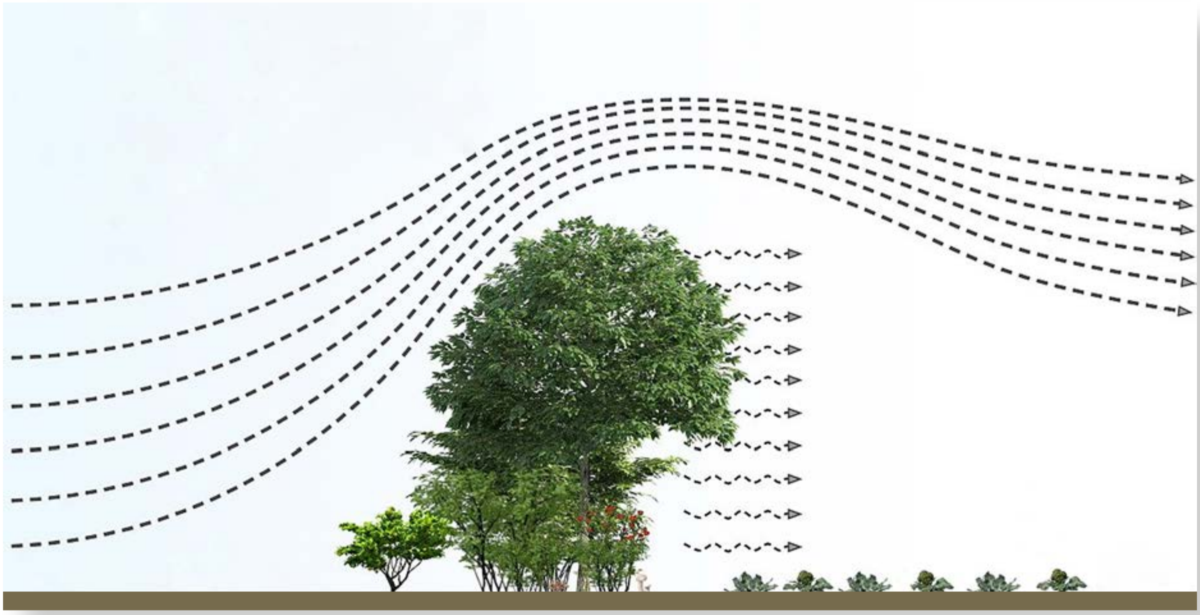


Figure 8 - Principle of an effective windbreak

The ideal is to reconstitute a park of mature trees to slow down wind speed more regularly. In the semi-arid tropical conditions of West Africa, the large Acacia albida nature parks that cover the cultivated areas generally protect these fragile areas from wind erosion quite well by reducing wind speed at ground level but also by depositing a large number of leaves on the surface.

To be used as a windbreak, forest species must have the following characteristics:

- evergreen leaves;
- rapid growth;
- a reduced space requirement;
- a root system such that root competition is limited.

Another method, which is inexpensive and well adapted to West Africa, is to sow lines or squares of millet or other fast-growing plant species in the middle of the rainy season that will ensure subsequent soil fixation. Full protection of these sites from grazing and fire is obviously essential to ensure the already difficult survival of the plantations, but light and supervised exploitation of crop production by herds after five years can be expected.

Installing sheeting as a windbreak

In the frequently experienced scenario where dangerous winds blow from several sides, it is better to use sheeting that is permeable to the wind, with a mesh of around 5 to 10 mm.

Figure 9 - Sheeting used as a windbreak

It is also possible to install smaller square plastic sheets at a height of 50 to 80 cm. In this case, they are installed by dividing the soil into a square grid, which will be smaller the more violent the winds are. The meshes can vary between 5 × 5 m and 8 × 8 m under typical conditions. However, plastic sheeting can be destroyed or made more fragile by UV rays after two years or so.

Fixing dunes

The aim is both to reduce the source of sands and to fix the dunes in place. In order to do this, both mechanical and biological fixation are required. Where the wind blows from a single direction, it is possible to stop wind erosion using lines perpendicular to the wind direction, at a distance of 20 times the height of the lines. For example, if millet or sorghum stalks with a height of 1 to 1.5 m are used, lines must be created every 20 m, otherwise the wind will pick up the sand in between these lines of defence. It is therefore necessary to have very large quantities of material, such as stalks of millet, oleander which grows in wadis, or palm and residue from cutting forests or shrub plantations located in the region.

4.1.3. Maintaining the quality of soils by liming

As a reminder, calcium plays a decisive role in the soil's physical fertility (stability of soil structures, sensitivity to surface sealing, gas and water exchange); chemical fertility (functioning of CEC, desalination); and biological fertility (activity of the microbial biomass). Calcium is also a nutrient for plants.

According to Hérody (1997), the essential role of calcium is not only to bind organic matter with clays, but also to regulate the mobility of metals, including iron, involved in organo-mineral binding. In soils that have developed such binding, liming improves structural stability; in other soils it limits the chemical reactivity of aluminium, iron and manganese and improves biological activity. However, liming should not be excessive, as it can be involved in retaining metals and other trace elements, as in chalky soils. For sound management of crop liming, it is practical to distinguish between maintenance and corrective applications.

STRUCTURE	**Stabilising the organo-mineral complex**
MICROBES	**Stimulating activity by offsetting acidification**
GEOCHEMISTRY	**Reducing toxicity by immobilising excess minerals**
PLANT	**Development and nutrition of plants**

The calcium content in soil varies constantly, and the important element is exchangeable calcium. The calcium content should be measured frequently and maintained at an acceptable level with respect to the type of soil dealt with. A distinction should be drawn between:

- chalky soils, which are always rich in active calcium
- soils that are not chalky but do have exchangeable calcium
- soils that are not chalky and have a low level of exchangeable calcium (most often on siliceous and acidic land).

Determining the level of the **exchangeable calcium** is essential to assess, together with the value of the cation exchange capacity (CEC), the proportion of calcium (the CEC's partial calcium saturation rate) and thus to be able to adapt liming strategies in acidic soils or soils with a tendency to become acidified.

This diagnostic method is less sensitive to seasonal variations than methods based purely on pH level.

Criteria for choosing a liming strategy according to the nature of the soil are summarised in Table 1.

Table 1: Criteria for a liming strategy

Criteria	Very acidic soil	Acidic soil	Neutral soil	Alkaline soil
pH water	>5.5	5.5–6.5	6.6–7.4	>7.4
pH KCl*	<4.8	4.9–5.5	>5.5	Not measured
Ca/CEC (%)	<40	35–65	65–100	>90
Total limestone (g/kg)	0	0	0–20	20–800
Active limestone (g/kg)	0	0	Close to 0	1–250
Liming policy	Corrective liming imperative (to avoid risk of aluminium toxicity) + Maintenance liming	Corrective liming required if pH <5.8 (if pH >5.8 to be confirmed by Ca/CEC ratio or S/T ratio) Maintenance liming in most cases	Corrective liming not necessary Maintenance liming according to Ca/CEC ratio or S/T ratio, or if structural condition of soil can be improved	Liming not necessary

*pH KCl: pH of a suspension of soil in a potassium chloride solution.
*S/T ratio = saturation rate of the complex.

Figure 10 - Liming a plot of land (heavy operation that may require a large amount of equipment)

When should liming not be carried out?

Soil should not be limed immediately after fresh manure or slurry is applied. Farm manure must not be spread on lime, as this triggers a chemical reaction that volatilises the ammoniacal nitrogen in the manure.

Liming must not be carried out in the 12 months preceding a potato crop (risk of gall, a disease caused by a soil fungus).

Liming should not be carried out before growing tobacco.

The effects of liming are never immediate, they become evident during the year or years following application. These soil improvers should never be applied without prior testing of the soil's requirements.

4.1.3.1. Maintenance liming

The aim is to preserve the calcic state judged to be satisfactory. This consists of the regular application (every three to four years) of an alkaline soil improver aimed at maintaining the pH and restoring to the soil the calcium and magnesium that have been used up over time. The quantities to be applied are evaluated according to exports from crops, leaching, and the acidifying action of mineral fertilisers. On average, the losses (exports + leaching) are about 15 to 450 kg/ha of CaO. It is thus generally advisable to apply about 350 kg/ha of CaO each year. The soil improver must work reasonably quickly in order to avoid a temporary excessive increase in the pH. Although this increase is unavoidable, it must be limited. Pulverised lime should be avoided as it works too quickly. If necessary, the dosage must be reduced and the frequency of application increased. The most suitable soil improver is crushed chalk. As maintenance applications can be predicted, they should be carried out before the crops that are most sensitive to a deficient calcic state. Conversely, liming should not be carried out before growing certain crops such as potato.

4.1.3.2. Corrective liming

The objective is to obtain a more favourable level of calcium. This involves adding a large quantity of alkaline improvers in order to restore the soil's pH balance. Corrective liming should be done only once during the season, in a single intake or possibly in several applications if the deficiency is very important and needs to be corrected in one operation. The amendment must ensure that action on the pH is fast enough to initiate the desired correction. In addition to the amount necessary for the correction, a few tons for maintenance until the next intervention can be added. The complete recovery of the calcium state will be gradual, because too much lime at once changes the characteristics of the soil too quickly. It is best to spread the pH adjustment over several years. The pH should not be increased by more than one unit at a time, as otherwise some nutrients may become trapped. Increasing the pH with the application of an alkaline soil improver reduces the availability of trace elements such as boron, manganese, zinc and, to a lesser degree, copper. Manganese deficiency is quite frequent, particularly in light (aerated) soils. A pH level that is too high, or excessive liming, increases the risk of manganese deficiency. Phosphorus in the soil also becomes unavailable at higher pH levels.

4.1.3.3. Products for liming

Calcium inputs are most commonly made up of lime and limestone. Raw products that can be used include ground limestone, chalk, dolomite, marls, industrial residue (sugar refineries), plaster or gypsum and various mineral fertilisers. 'Cooked' products are heated to 900 or 1,000°C; this process is used to obtain quicklime (calcium oxide or magnesium) and slaked lime (calcium hydroxides).

As a general rule, raw products are cheaper, and are therefore used much more frequently than cooked products, but they work less quickly. Equally, a fine lime is more expensive than a coarse lime, but it will work more quickly. However, this reactivity is a double-edged sword as it leads to more risks of retention and higher sensitivity to leaching. In order to avoid these disadvantages, cooked products should be reserved for small doses of annual inputs, not exceeding 500 kg/ha of raw product in sandy silty soil.

The choice of a product should take account of the cost of the different soil improvers by neutralising unit (see Box); the soil's magnesium content; and the desired speed of action.

What is the neutralising value?

The contents of the liming material are expressed in CaO equivalents, even if their chemical formula is different. By convention, 1 kg of CaO is equal to 1 neutralising unit.

The effectiveness of liming material is determined by its neutralising value (NV) and its speed of action. The NV corresponds to the number of CaO equivalents that have the same impact on the soil as 100 kg of the soil improver in question. The NV is thus expressed in kg CaO/100 kg of product.

Magnesium oxide (MgO) has a higher NV than calcium. This means that 1 kg of MgO is equal to 1.4 CaO equivalents or neutralising units.

The speed of action is assessed by the fineness of grind and the carbon solubility. Carbon solubility is a measurement in a laboratory of what happens in the field in terms of the dissolution of the product. It is expressed by a number between 0 and 100. The finer the product, the more quickly the pH increases and the acid level reduces, so the NV of the product will express itself more quickly.

The following raw products can be used:

- **Dolomite** (or Magnesian Limestone) can only be justified on soils that are low in both calcium and magnesium. In this form, the magnesium becomes available quite slowly. For fast action, sulfate forms such as kieserate should be chosen.
- ***Lithothamnium calcareum*** is very calcareous alga of the Corallinaceae family, with a concentration of many minerals and trace elements. *Lithothamnium* is considered to be a 'noble' product, high in magnesium and trace elements (including boron, cobalt, copper, iodine, iron, manganese, selenium, sulfur, zinc, etc.). With the equivalent fineness, it is faster acting than an ordinary limestone, but is rarely used as it is considerably more expensive than other soil improvers. It is used more often to fertilise soils in organic agriculture as, according to those who favour it, it restores the biological, chemical and physical balance of the soil by increasing microbial activity and the humidification process. It also seems to reinforce the resistance of plants to diseases and insects.
- **Marls** are a very heterogeneous family of products in terms of their limestone content (which can vary from 30 to 70%) and the quality of the clays. They can be added in high doses but their cost is also high.
- **Coarse limestones** are ultimately the most attractive and cheapest products, but are unfortunately not the easiest to find on the market; they are known as 0–2 or 0–4 to indicate that the particles are smaller than 2 or 4 mm. They contain quite a large fraction of powder which is effective from the first year, and the coarser fraction is gradually attacked according to microbial activity. These products cannot be leached and do not run the risk of causing retention.

In **organic agriculture**, the products authorised by regulations are mostly calcium carbonates of natural origin, in other words more or less pure calcareous rocks with varying degrees of hardness and grind.

The product will work more quickly the softer it is (for example chalk), and the more it is reduced into a powder. The 'impurities' contained in limestone can be very favourable if they correct a deficiency in the soil: commercial products tend to promote magnesium found in dolomitic limestones. There are also phosphate limestones, ferruginous limestones, potassium limestones and clay limestones (marls). Any **accessory nutrient** is favourable if it corrects a deficiency, and becomes harmful if it increases a natural resource.

4.1.4. Managing the risk of soil salinisation

There are several ways to prevent or correct salinisation: better water management (saving soil water and using irrigation where necessary), leaching, drainage and flooding the land.

4.1.4.1. Better use of irrigation water

Spray irrigation is more effective than surface irrigation, but it can also deposit salts directly on the plant if the irrigation water is saline. It is preferable to practise drip irrigation that measures the quantity of water distributed on the surface around the plant. Some crops can tolerate salt better than others. But sometimes farmers – or even entire regions – need to rethink their crop system to make it more profitable. In Cape Verde, for example, farmers have abandoned sugar cane crops, which require a lot of water, in favour of high-value horticultural crops such as tomatoes, watered by drip irrigation.

4.1.4.2. Leaching

By giving crops just a little more water than necessary – but without overdoing it – salinity is reduced in the root area and the salts are dissolved and transported to the aquifer layer which disperses them, provided natural drainage is sufficient.

4.1.4.3. Drainage

Ditches or underground pipes can carry saline water away. A third of waterlogged saline land could be improved through better drainage and a whole series of techniques geared to the local situation. For example, over the past 30 years the Egyptian national drainage programme dealt with soil that is water-saturated and saline by using different types of drainage and pumping stations, which made it possible to facilitate the flow and reuse of drainage water.

4.1.4.4. Flooding

Land overloaded with salt that has become unsuitable for cultivation can sometimes be rehabilitated through **submersion and drainage**. This method, which is often expensive, may be worthwhile depending on the value of the land and crops, as restoring the productivity of agricultural land makes it possible to capture carbon found in the atmosphere. In cases where the land is still somewhat productive, farmers can sow a crop that tolerates a certain degree of salinity and requires a large quantity of irrigation water, such as rice. In some cases, flooding land also has a beneficial effect on reducing pest populations in the soil. For example, soil nematodes need oxygen to survive; and some anaerobic bacteria such as *Clostridium* release toxins that destroy nematode larvae, cysts or eggs).

4.1.5. Preventing soil compaction

Soil degradation and soil improvement vary according to the location, land use and objectives of those practising agriculture. The solutions proposed to resolve soil compaction problems can be grouped into two categories: **preventive** measures and **curative** measures.

Prevention entails employing conservation measures to maintain the soil's productive qualities. According to AGRIDEA (2014), preventive measures are based around three pillars:

- planning cropping interventions
- limiting the loads borne by the soil
- controlling the physical properties of the soil.

4.1.5.1. Planning cropping interventions

- **Adapt the type of farming to the land**: Large crops and intensive farming (e.g. five to six cuts for pasture) should be carried out on deep soils that dry well.
- **Practise targeted tillage of soil**: The more intensive the tillage of the soil, the more the soil's structure loses its load-bearing capacity. Soil turning should therefore be limited, the soil should be tilled to as shallow a level as possible, and the intensiveness of tilling should be minimised (reduced speed for tractor-driven machinery, reduction in surface area tilled).
- **Diversify rotations or succession of crops over time**: Combine or alternate main crops that have roots of different depths (e.g. lettuce, 30 cm; okra, 60 cm; maize, 90 cm; amaranth, deep taproot), catch crops (those planted between two main annual crops), and green manure crops (e.g. *Tithonia diversifolia*, *Prosopis africana*). Cropping systems should be selected that include crops, pasture plants and, where appropriate, agroforestry plants with strong primary roots (dense and fibrous root systems) able to penetrate and break up compacted soils.
- **Apply short fallows**: Plant fast-growing agroforestry species capable of generating good quality leaf biomass over a period of one or two years in order to restore soil fertility (e.g. *Sesbania sesban, Gliricidia sepium*).
- **Consider the harvest date as a risk factor**: For example, a late harvest reduces the probability of good soil conditions (if the soil is drier at harvest time).
- **Plan the harvest**: If humidity conditions are critical, limit the load volume and unload the harvest more often (e.g. make several piles).

4.1.5.2. Limiting loads borne by soil

- **Reduce vehicular traffic**: All loads on soil should be reduced to the absolute minimum, particularly on bare soils. Reduce the number and frequency of cropping interventions, and perform agriculture or forestry operations only when the soil humidity content is suitable, down to the deepest depths. The wheels of irrigation pivots also contribute to the risk of soil compaction.
- **Maximise the contact surface of tyres with soil**: Choose tyres that are as large and as wide as possible, use twin wheels, opt for tandem or Kurmann axles for self-loading trailers or slurry spreaders.
- **Adapt machines and vehicles the soil's load-bearing capacity**: Have a system to regulate tyre inflation pressure (if possible, keep tyre inflation pressure under 1 bar). The regulation system allows the tyres to be deflated slightly. This increases the contact surface when machines move over the land. The aim is for the tyre to be deformed by the land – not the reverse. In order to drive on roads, the tyre pressure must be restored (except for special tyres).
- **Choose machines according to size and weight**: Avoid using excessively large machinery, and where possible avoid using machinery altogether.
- **Prepare for vehicle passage**: Always keep an eye on the load per wheel, particularly during harvests and when spreading farm manure. In principle, loads of more than 3 tonnes should be used only in good conditions (dry soil and good tyres).

4.1.5.3. Controlling physical properties of soil

- **Evaluate soil moisture content**: Moisture content should be evaluated based on the weather conditions of the preceding days. After heavy precipitation, the soil must be left to dry sufficiently before driving on it.
- **Maintain adequate organic matter in the soil**: This is done in order to improve and stabilise the soil structure.
- **Use farm manure, green manure and crop residues**: The regular spreading of manure or compost and the practice of direct sowing are better for soil structure and stimulate biological activity in the soil.
- **Monitor pH**: On surfaces with a low pH (<6.2) use fertiliser with an alkalising effect or maintenance lime. A neutral pH favours the load-bearing capacity of the soil and good conditions for living organisms and their aggregating activities.

4.1.6. Avoiding soil pollution

Farmers have difficulty in protecting themselves against atmospheric pollution, other than by choosing not to establish themselves close to an exposed area. We are seeing a significant increase in urban and peri-urban agriculture (25 to 30% of production today). Urban soils are often highly contaminated, so they must be monitored closely for potential contamination of products harvested in these cultivation areas.

4.1.6.1. Adopting environmentally friendly crop management and plant protection practices

Crops such as palm oil, rubber trees or cacao trees, which have been established for many years, are often spatially concentrated in production basins where they are dominant, or areas that are almost exclusively dedicated to one crop. Pests encounter particularly stable and favourable conditions in such locations. This is also largely true for vegetable crops, as it is often the same crops that cover the soils at the same time (e.g. tomato, onion, cabbage).

Repeated use of the same pesticides to control infestations encourages the appearance and development of populations resistant to those pesticides, and leads to the disappearance of natural antagonists, leading to repeated treatments (**vicious circle of pesticides**).

With better knowledge of the plot, the variety cultivated, the plant's risks and needs at the different stages of development, beneficial organisms and potential plant health problems, the intensity of treatment can be adapted to the development cycle and spatial distribution of the pest, or precision treatments can be carried out (spot treatment of weeds or disease outbreaks), or selective and less persistent active substances can be chosen. This makes it possible to reduce the frequency of treatments and the doses applied per unit of surface area.

In order to reduce pressure from chemical pesticides on soils, **integrated pest management** (IPM) should be used, and where possible, biopesticides (biocontrol agents) and biological control technologies should be favoured[30]. These include:

- treatment via introducing and acclimatising natural enemies of pests via dispersal in large quantities (inundative application) or small quantities (inoculative application)
- environmental manipulation that aims to encourage natural enemies of pests that are naturally present (beneficial organisms).

4.1.6.2. Intercepting flows of pollutants at farm level31

The main ways in which pesticides and their residues are dispersed are drift from drops when applied, infiltration into the soil or underground waters, and run-off into surface waters. Spread due to wind has the effect of contaminating the surface of the area close to the site. Dispersal by infiltration leads to contamination of the soil below the storage site; this can lead to the contamination of groundwater and, if it continues to spread, contamination of surface water (e.g. lakes and waterways).

These flows of pollutants can be limited by strictly adhering to good plant protection practices, using anti-drift nozzles, maintaining unsprayed buffer zones, and setting up installations (grassy strips) that will favour the infiltration of residual water from spraying. Buffer zones made up of grassy or wooded strips can be installed to protect surface waters (e.g. along rivers, wadis or ponds). Their effectiveness varies widely, from very poor to almost 100% interception of pesticides.

30 See COLEACP Handbook on *Foundations of Crop Protection*.
31 *Idem.*

4.1.6.3. Controlling pollutants on the farm

It is possible to manage pollutants (hydrocarbons, oils, pesticides, chemical fertilisers, biocides, etc.) through efficient storage in well equipped premises, with a retention basin to avoid external leaks. Farmers must be able to manage their waste and effluent (e.g. tank bottoms) adequately. Dangerous waste must not be burnt and, above all, never buried in the soil at the farm.

4.2. RESTORING SOIL FERTILITY

We have seen the key role played by organic matter in soil. All techniques aimed at improving or preserving soil fertility have one aim in common – **enriching the soil with organic matter**.

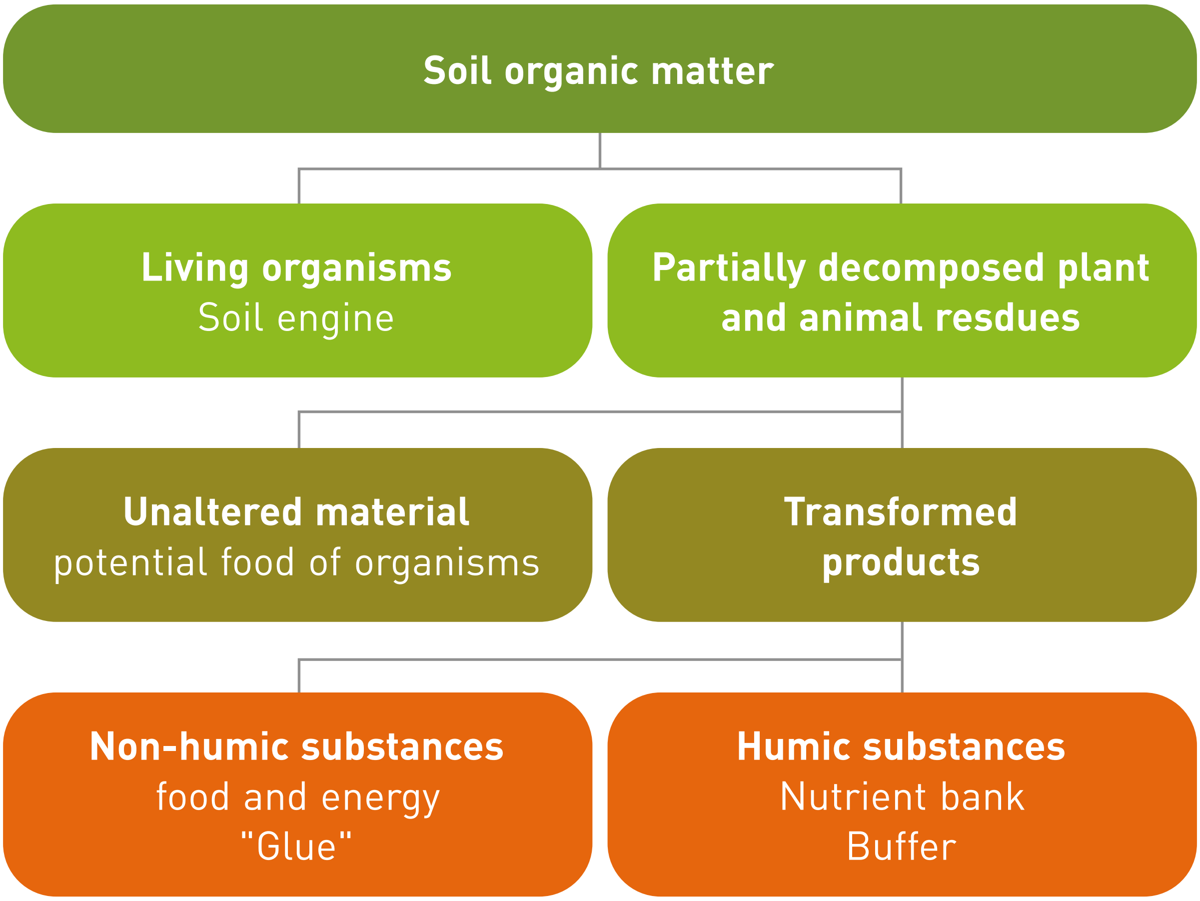


Figure 11 - Potential beneficial effects of organic products on soil and crops (Source: A.J. Bot, FAO)

4.2.1. Soil mulching

Mulching consists of covering all or part of a degraded plot of land with organic matter[32], for example plant residue, straw, tree bark, vegetable tops or tree leaves, in order to implement revegetation and rebuild the soil by maintaining the humidity and the development of biological activity (source of carbon).

Mulching has many objectives (van Schöll, 1998):

- **stimulating organisms** in the soil (adding digestible organic matter)
- **protecting** the soil from water and wind erosion and dehydration
- improving **infiltration**
- increasing the level of **humidity** in the soil.

Combined with increased infiltration, this makes it possible to maintain a higher level of humidity than in soils without a layer of mulch (Dapola Da, 2008). The impact of mulching on reducing water evaporation from soil has long been recognised. Numerous plant materials have been studied to assess their potential effectiveness as mulch. The effectiveness of mulch against evaporation mainly depends on its thickness: the thicker the mulch, the more evaporation is reduced. Well mulched plants will suffer less quickly from a lack of water during the dry season (Unger, 1989).

Studies carried out on the minimum tillage of soil show that a livestock bedding cover vastly reduces extremely high surface temperatures. Bare soil in tropical regions can sometimes reach very high temperatures during the day (as high as 50°C), which negatively affect crop growth (CTA, 1995). A layer of mulch protects the soil from the sun and lowers the temperature during the day, which favours seed germination and the growth of roots and microorganisms (van Schöll, 1998).

32 Mulching with other materials (e.g. plastic or gravel) is possible, but the objective is then mainly to prevent the growth of weeds.

Figure 12 - Banana trees and maize with mulch (Source: FAO)

Crop residues such as straw, maize stalks, banana leaves or palm leaves can be used as mulch. However, it is important not to encourage the conservation or spread of certain fungal diseases through mulch. This is the case for black sigatoka, a leaf disease that affects banana plants. If the infected leaves cannot be removed from the plantation, they may be placed on the ground, but they must be placed on top of each other (the upper surface of the leaves towards the ground) in order to limit the emission and dispersion of ascospores, which are spread via wind and rain from plant to plant and from plot to plot.

Material taken from hedges must be reduced to pieces of less than 10 cm. The residue is placed on the surface of the ground and covered with a thin layer of soil so that it is not blown away by the wind. If a crop is to be sown or planted, the mulch should be pushed to one side and the seeds or seedlings placed in the soil.

Mulch should be applied in layers that are not too thick in order to prevent fermentation and consequently the build-up of high temperatures.

In tropical regions, a mix of vegetation that decomposes slowly should be favoured, in order to keep the soil covered for as long as possible. The installation of evergreen hedges can be used to protect crops from fire in these climates.

4.2.2. Associated cropping

Associated cropping can be defined as the **simultaneous cultivation of at least two crops on the same plot** during a significant period of their growth, but without necessarily being sown or harvested at the same time (Vandermeer, 1989 and Willey, 1979, quoted by Ndzana Abanda, 2012).

There are different types of associated cropping:

- **mixed cropping**: the different crops are sown together
- **intercropping**: the different crops are sown in interspersed lines (e.g. cassava can be a secondary crop between lines of banana trees; tubers such as *Colocasia* and *Xanthosoma* can be grown under banana trees)
- **relay cropping**: the secondary crop is sown after the main crop has been harvested (e.g. sorghum and pigeon pea are often grown together in India; after the sorghum is harvested the peas grow through the sorghum stubble).

This system has the disadvantage of giving rise to interspecies competition for light, water and nutrients, and it contributes significantly to rapid depletion of the soil. However, associated cropping does make it possible to obtain many agricultural resources in a short time in the same area.

When done well, it can lead to an improvement in fertility, as many plants can be combined due to their complementary needs. It can also play a particular favourable role, such as protection against pests and diseases. The combination of maize and beans (or peas) offers two beneficial effects: maize acts as a prop for beans, while beans provide the maize with nitrogen. Onion flies are repelled by carrots, as their scent repels the flies; and carrots are also useful to plant between rows of celery in order to combat leek moth. The combination can also be neutral (no additional beneficial effect expected); and sometimes the combination is actually unfavourable and should be avoided (Table 2).

Table 2: Some examples of plant combinations

Species cultivated	Associated crop	Favourable combination	Unfavourable combination
Garlic	Tomato, carrot, spinach	Fruit trees	Bean, pea
Asparagus	Tomato, pepper	Not known	Not known
Aubergine	Bean, lettuce, onion	Garlic	Tomato, carrot
Carrot	Bean, cabbage, pepper	Rosemary	Beetroot
Celery	Bean, leek, garlic, cabbage	Spinach	Potato, maize
Cabbage	Bean, cucumber	Celery, rosemary	Garlic, onion
Cucumber	Cabbage, pea, maize	Not known	Not known

Associated cropping is practised in tropical regions under all soil and climate conditions. The main advantages are as follows:

- **Making better use of nitrogen** drawn from the air by legume species (beans, peas, clover, etc.), which is released into the soil as the roots decompose. When nitrogen-fixing bacteria (*Rhizobium*) are found in the soil, the **symbiosis** between the leguminous plants and these nitrogen-fixing bacteria gives the plants access to a constant source of bacteria and provides them with an advantage over species that depend purely on nitrogen from the soil. Nitrogen-fixing bacteria provide plants with atmospheric nitrogen in exchange for carbon generated by photosynthesis.
- **Benefiting from protective effects** against diseases and pests. For associated crops, it is important to ensure that only species that stimulate each other, or at least that do not disrupt each other, are grown together. When crops are combined, it is possible to improve agronomic performance, for example by reducing the proliferation of weeds and attacks from diseases (Hauggaard-Nielsen *et al.,* 2009) and some pests (e.g. root nematodes).
- **Making better use of the soil**, which will now be more productive. Different types of experimental work carried out in order to study how associated cropping works show that in general there is a better uptake of resources in the environment for combined crops compared with single crops, leading to higher productivity (Hauggaard-Nielsen *et al.,* 2009).

4.2.3. Adding organic matter to the plot

Adding organic matter to the soil is the most effective way of increasing its quality. Organic matter should be considered not only as a fertiliser, but also – or perhaps first and foremost – as a soil improver.

Organic matter can be applied to the soil in different ways, particularly through the use of composts, cover plants (alive or dead), and green manure crops. It can be added in various forms, fresh or matured (cf. the section on 'organic soil improvers' below).

Composts

Adding compost is the ideal way to improve the **quality** of the soil, increase its richness in **organic matter** and obtain a good balance of **minerals**. When starting a compost heap, the best way to achieve mineral balance is to define, through soil testing, which quantities should be added as crushed minerals, such as natural phosphate, crushed basalt, potassium sulfate, gypsum, etc., to the composting materials. The biological processes that form compost will make these minerals easily available to the plants in both rapid- and slow-release forms. The resulting compost, which is rich in minerals, is spread over the crops. The quantities to spread can vary on average between 10 and 20 t/ha.

We can thus regularly apply trace elements mixed with molasses and/or microbial improvers infused for several days in order to make them bio-available. They can be sprayed on the fields, as the sprayer ensures homogeneous distribution over the entire field. The aim is for most of the nutrients to penetrate into the soil. This system guarantees that the soil's biological activity releases a constant quantity of all the nutrients required by the crop and makes it possible to obtain a good yield. The exhaustive nature of the nutrition programme guarantees the absence of deficiencies.

Green manure

This is a crop grown with the sole purpose of improving **soil fertility**, but other effects can be obtained, for example **combating erosion**. These soil cover plants are also effective for preventing weeds (competition effect), and the fact that the soil is covered by these plants is a determining factor in the reduction of run-off. The protection of the soil surface afforded by livestock bedding or well developed plant cover makes it possible to reduce erosion and loss of water due to run-off, and to slow the development of crusts. The rapid establishment of crops and the development of a biomass suitable for effectively intercepting rain should be encouraged.

Fast-growing plants that store large quantities of minerals in young tissues are used as green manure. Before planting the next crop, the green manure can be dug in by tilling the soil or left as a mulch on the surface.

Several species of annual legumes with non-edible seeds, such as velvet bean (*Mucuna pruriens*), kudzu (*Pueraria phaseoloides*) or lablab (*Lablab purpureus*), are used as cover plants to control erosion caused by water, combat weeds and restore soil fertility. Other than legumes, *Tithonia* (Mexican sunflower, *fleur jalousie* in Cameroon) is also very popular.

Studies carried out in Africa (e.g. Fairhurst, 2015) have shown that adding to the soil mulch from fast-growing perennial leguminous plants such as leucaena (*Leucaena* sp.), pigeon pea (*Cajanus cajan*), sesban (*Sesbania sesban*) or gliricidia (*Gliricidia sepium*) significantly improved its fertility.

Green manure has the advantage of taking assimilable elements available in the soil and storing them in the biomass while awaiting the next crop. This can prevent losses (particularly of nitrogen) through leaching, and the pollution of the water table (fewer nitrates than in underground water).

Green manure mineralises quickly because it is made up of young tissues, and it frees up minerals for the next crop. The mineralisation of the fresh organic matter is almost complete, and it is generally accepted that green manure has rapid positive effects on nutrition but few direct long-lasting effects on the soil's organic matter content.

Green manure improves yield

A broad meta-analysis carried out across the African continent by the World Agroforestry Centre (Sileshi *et al.*, 2008) showed that green manure significantly improved yield (e.g. of maize), either alone or with small quantities of mineral fertiliser:

- Green manure has **synergetic effects** with mineral fertilisers and produces **acceptable yields** with relatively modest expenditure on fertiliser imports.
- Green manure **reduces production risk** by stabilising the yield, compared with a crop that has not received manure, or maize grown after traditional fallow periods.
- Green manure gives good results where they are most needed, on lands with low or average potential, making it suitable for poor farmers who are unable to obtain mineral fertiliser.

According to this study, maize grown with green manure produced significantly more seeds than maize grown without fertiliser (the usual practice of subsistence farmers) or maize grown after a traditional fallow. Green manure increased the average yield by up to 1.6 t/ha compared with the practices of small-scale farmers. The maize yield was more stable in fields using green manure than in unfertilised fields or in fields where maize was grown after traditional fallow periods; nevertheless this yield was not as high as that of the fields that received mineral fertiliser. With respect to maize yield, the production risk is thus lower in fields using green manure than those subject to farmers' practices. Finally, the maize yield increased by over 30% when green manure plots received a soil improver consisting of mineral fertiliser at half the recommended dose, compared with similar plots that did not receive any soil improver. Larger increases in the maize yield were recorded by using green manure on sites with low to average potential than those with a high potential.

Manure

Among the different types of farming effluents, only manure is an organic soil improver. Liquid manure (liquid that runs out from livestock bedding) and slurry (mix of solid excrement, urine and water) are more closely related to organic fertilisers. They are rapidly mineralised and their main role is not to improve the structure of the soil, but to **add nutrients**.

During its maturation (which can take several months), animal excrement naturally loses some of its nutrients. Carbon losses are inevitable, but at the same time necessary for the good health of the bacteria that use this organic matter. The more serious losses are nitrogen losses in the form of gaseous ammonia. These losses are difficult to prevent on the farm, but are easy to control if the manure is packed down well when it is piled up. Potassium losses can turn out to be catastrophic, but it is easy to avoid them by carefully collecting the liquids that flow from the pile, and limiting these flows by protecting piles from leaching caused by rain. **Manure heaps should be set up on leak-proof platforms, never directly on the soil.**

Obtaining good manure starts in the cowshed, where it must be ensured that the livestock bedding, which is well moistened with urine, is as well packed as possible so that anaerobic conditions can become established, guaranteeing lower losses of carbon, potassium and nitrogen. The open-yard technique could offer good conditions if the animal housing contains a lot of straw, which is not often the case.

The composition of manure depends on several factors, including the species of animal, its diet (especially the minerals), the type of straw the excrement is mixed with, and the state of development of the product (fermentation). The quantities to spread can vary from 20 to 50 t/ha for bovine manure heaps and from 3 to 10 t/ha for poultry manure heaps. The physical characteristics of manure heaps and composts (dry matter content, density, cohesion and internal friction) vary considerably from one product to the next. Cow, sheep, pig, goat or horse manure heaps are usually deficient in phosphate. By contrast, poultry manure heaps are very rich in nitrogen, phosphorus and potassium. Other than the major nutrients, these products also provide considerable quantities of other elements (sulfur, sodium, trace elements). It should be noted that poultry effluent (manure and droppings) is generally considered 'soft manure', which acts rapidly but does not have the same quality.

Because manure is deficient in **phosphorus**, farmers should supplement it by treating the livestock bedding, for example with calcium phosphate (natural phosphates or maerl). Other than the desired supplementation, phosphates and calcium heavily deodorise the livestock bedding, making it possible to avoid the proliferation of undesirable bacteria that carry diseases such as mastitis, foot rot, diarrhoea, septicaemia, etc. Finally, in order to be useful, manure must be composted and incorporated into the soil at the right time. Unfortunately, manure heaps are often poorly prepared and poorly used by farmers.

Figure 13 - A heap of manure – as is often the case, this heap is poorly compacted, and a manure heap should never be located directly on the soil

The most frequent methods of manure composting are composting in heaps and surface composting. This type of composting must convert organic matter maintained in an anaerobic state into a state of microaerobic decomposition. These conditions force the bacteria to respire some of the intermediate molecules that they have created. These conditions make it possible to recover ammonia, urea nitrogen and various other compounds, which are reincorporated in the bacterial organisms and are therefore not lost. Other elements such as phosphorus or sulfur are also better preserved under these conditions.

- **Composting in manure heaps** is accompanied by a high increase in the temperature at the heart of the heap. This high temperature eliminates a large number of undesirable or pathogenic microorganisms and bad seeds. In addition, the formation of humus in heat is more intense than that under cold conditions. After about two weeks, the manure loses its odour, and at that point it is a young compost that could already be used. However, it is better to use a compost that has matured for two to three months.
- **Surface or soil composting** consists of spreading fresh manure, or a young compost, in spray form on bare soil, or better still on green manure or grassland. This technique offers various advantages compared with windrow composting. It intensely stimulates bacteria in the soil, particularly *Azotobacter* (free-living soil bacteria which are aerobic and able to fix nitrogen non-symbiotically, without having to be attached to the plant roots in the nodules). Through their atmospheric nitrogen-fixing effect, *Azotobacter* massively offset nitrogen losses, which are generated in larger amounts by composting on the soil than by windrow composting.

Manure is still misused far too often. The idea that manure that is quickly dug in will decompose more quickly, and the nutrients released will be used by the plants, still persists among many farmers. Most farmers have the tools to spread manure on the surface, but often the time between the moment when they spread the manure and the moment when they till the earth and dig in the manure is too short – an interval of several weeks, or even several months, is advised, depending on the maturity and composition of the manure, average temperature and rainfall. In order for the manure to be integrated into the soil more rapidly, the soil can be gently scarified in order to mix the manure with the topsoil (this will speed up its maturation). After a few weeks, once it is no longer possible to distinguish the nature of the initial materials (e.g. straw), the soil can be tilled and the manure can be buried more deeply. It is preferable to avoid spreading manure just before sowing certain crops (e.g. maize).

Liquid manure and slurry

Although animal urine is an excellent precursor to fertiliser application, it is often used very poorly and can pose more problems than it solves. Firstly, urine is very low in phosphorus and calcium. In addition, urine is considered **acidifying** (but the problem mainly arises from poor management of nitrogen). This acidification is quickly fatal to soil bacteria and *Azotobacter*.

Unless it is mixed with straw or other plant residues, which are vital sources of cellulose for the bacteria, urine alone does not stimulate bacterial life in soil. Finally, incorporating urine into the soil leads to massive **nitrogen losses** in the form of ammonia, as well as substantial **potassium losses**. This is why it is preferable not to spread it on land 'as is'. If a decision is still made to spread it, the least harmful way of preparing liquid manure and slurry is to oxygenate it to maintain aerobic activity in the storage pits, to add phosphates, and to dilute it. Finally, as for all nitrogen fertilisers that run the risk of polluting water, it should be sprayed at least 6 metres away from waterways, lakes or other surface waters.

4.2.4. Fallowing

Fallowing (known as natural fallowing) has been practised by farmers since time immemorial. It consists of temporarily interrupting the farming of a field or part of a field for several months or years in order to encourage the restoration of soil fertility.

So-called 'improved' fallowing is a rotating system in which carefully chosen species of trees or shrubs are used as fallow species in rotation with crops in order to improve the soil fertility or to produce economic goods. The principle of improved fallowing involves planting, in combination with food crops, species of trees or shrubs that improve the soil, generally fast-growing leguminous plants. After the food crops are harvested, the soil-improving species or leguminous plants are left in the fields during the fallow period. During this fallow period, the trees or shrubs use their extensive root systems to absorb large quantities of nutrients in the upper layers of the soil, at the same time as fixing atmospheric nitrogen. These nutrients, drawn from the deep soil layers and the atmosphere, then return to the surface of the soil and improve soil fertility through falling leaves and the decomposition of roots and branches.

There is a difference between improved shrub fallow and improved tree fallow (Sado, 2008).

Improved shrub fallow

This is a natural fallow in which one or several species of fast-growing nitrogen-fixing shrubs are introduced (e.g. *Cajanus cajan*, *Sesbania sesban*, *Tephrosia* spp.) in order to speed up the restoration of soil fertility, to shorten the fallow period, and to improve the production of annual crops. As well as improving fertility, these plants also provide some important ecosystem services for populations (combating erosion, medicinal plants, firewood, food, fodder, etc.).

For example, the introduction of *Cajanus cajan* (pigeon pea) in a field of maize does not require any additional maintenance work. The only maintenance operations required are weeding and mounding, which are usually carried out by farmers in their maize fields. During the fallow period –after the maize is harvested – the pigeon pea stalks that remain in the field do not require any maintenance. After the maize is harvested, the pigeon pea is left in the field where it continues developing until it produces fruit.

Figure 14 - Pigeon pea or Angola pea (Cajanus cajan) (Source: ILRI)

The seeds are ripe when the pods start to lose their green colour, and it is recommended that the peas are harvested as they reach physiological maturity. When the pods dry in the field, they explode and let the peas fall, which makes harvesting them difficult and leads losses.

After the pigeon pea stalks are harvested, at the end of the fallow period, the pigeon pea stalks are cut (forest area) or uprooted (humid savannah area), and are spread over the field. When all the leaves have fallen under the effect of the sun, the stalks can be gathered up and placed in a pile. The field can then be cultivated, taking care to mix all the leaves into the soil. The pile of pigeon pea stalks can be used as firewood. They can also be burnt on site and the ashes can be used to fertilise the field.

Improved tree fallow

This is a period of natural fallow in which one or several species of nitrogen-fixing trees that do or do not fix nitrogen are introduced to accelerate the restoration of soil fertility, to combat erosion, and/or to obtain various products (fruit, fodder, wood etc.).

For example, calliandra (*Calliandra calothyrsus*), a nitrogen-fixing tree that originates from Central America and Mexico, originally introduced to Indonesia to create shade for coffee, is useful for fodder and firewood, and to restore soil fertility. Calliandra prunings are used to feed cattle, and it is also a good source of honey. Food crops are planted in corridors between the lines. The spacing can be adapted to local conditions, but bearing in mind that Calliandra's effectiveness in fertilising the soil is reduced when spacing is increased.

Figure 15 - Calliandra calothyrsus (left) and a plantation with tree fallow (right)

4.2.5. Techniques for soil decontamination

Unfortunately there are very few techniques, other than extraction of the polluted mass, for soil decontamination. Thankfully, for organic compounds soil microbes can 'digest' the molecules, provided they are bio-available and not adsorbed by the soil (known as **bioremediation**), and for heavy metals some plants can extract them from the soil and concentrate them (known as **phytoremediation**).

4.2.5.1. Bioremediation

Bioremediation is a technique to increase/accelerate biodegradation or biotransformation by inoculating specific microorganisms (bio-augmentation) or, preferably, by stimulating the activity of indigenous microbial populations (mostly bacteria) by supplying nutrients and adjusting the environmental conditions (air, temperature, sources of carbon and nitrogen, moisture, pH, etc.)

Bioremediation is used to decontaminate a natural site (soil, sediment, surface or underground waters)[33], using microorganisms, fungi, various plants, or enzymes that they produce. The methods used are therefore environmentally sound and safe for human health. These organisms are used, for example, to degrade nitrates and phosphates, to combat oil spills, to degrade asbestos, to reduce the propagation of heavy metals in various wetlands, or even to degrade pesticide residues in water and soil.

33 Chapter 10 of the COLEACP Handbook *Foundations of Crop Protection* presents this technique as a way to treat the dregs of tanks, waters contaminated by pesticides (biofilters, biobeds, etc.). It also explains in detail how biofilters work.

4.2.5.2. Phytoremediation

Some plants are known for their ability to absorb heavy metals (arsenic, cadmium, copper, lead, zinc, etc.) through their root system (some capture it in the air through their leaves). In some cases the pollutants are merely neutralised, but in other situations they can be rendered easily extractable. During a phytoremediation process, the plants acting on the pollutant act at different levels. Pollutants can be stabilised, degraded or sequestered in the rhizosphere, or even rendered volatile and eliminated in the surrounding air.

The plants considered for pollution control must grow quickly, produce a large amount of biomass and be competitive with plants that are endogenous to the site. They must also tolerate pollution in order to enable optimum extraction of the pollutant. The plants will be chosen according to their properties (density of root cover) in relation to the type of mechanism considered for pollution control.

Four main mechanisms are implemented according to the nature of the pollutant and its physicochemical characteristics (Figure 16): (1) phytoextraction; (2) phytodegradation and phytosequestration; (3) rhizodegradation or biostimulation; and (4) phytostabilisation.

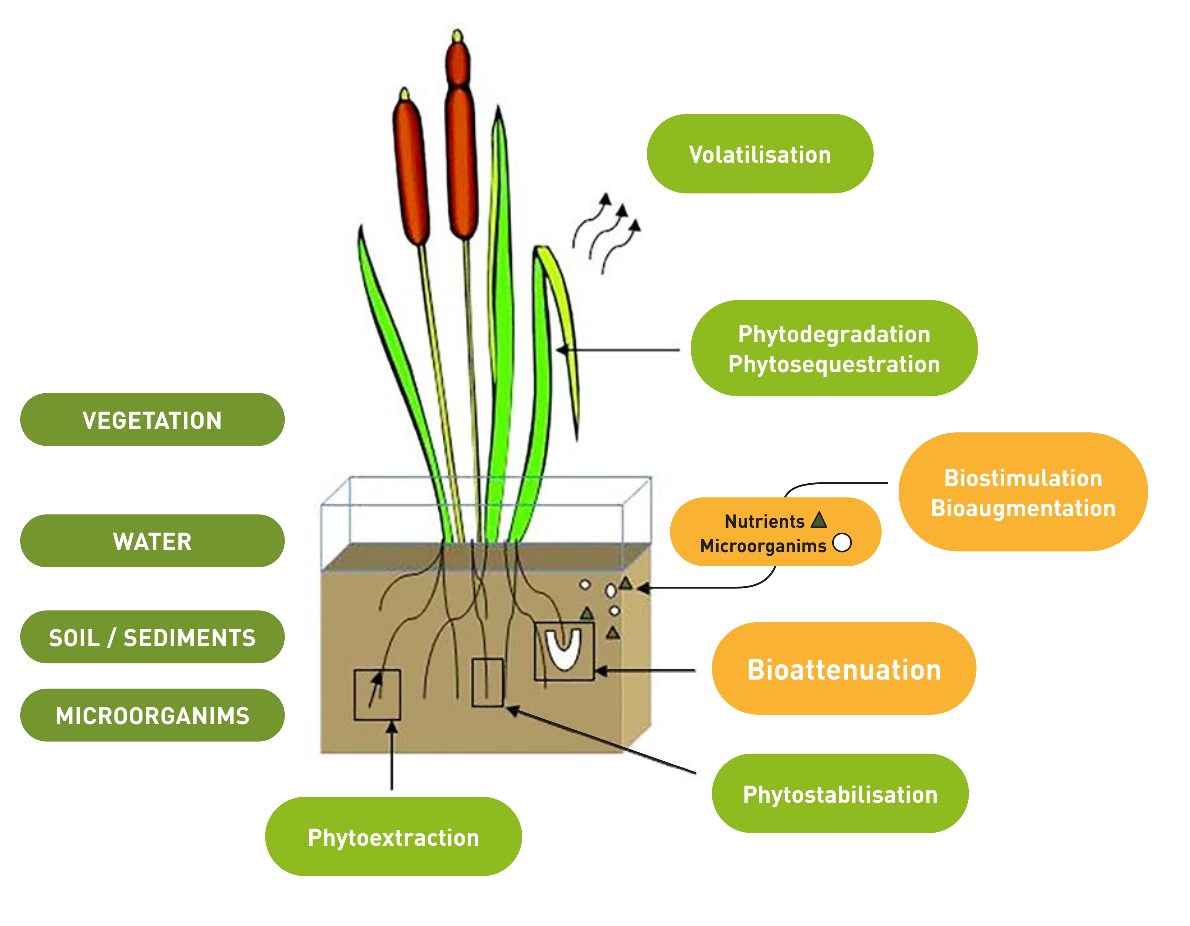


Figure 16 - Mechanisms implemented in bioremediation or pollution control in plants

Phytoextraction

This mechanism is based on the ability of plants to extract and accumulate pollutants found in soils. The result is the absorption and accumulation of pollutants in tissues above ground, without involving their degradation. At the end of this process, the parts of the plants above ground need to be harvested. The pollutants can then be destroyed via incineration, but also through composting. In the case of phytoextraction of heavy metals, the plants considered are those with the highest levels of absorption, translocation and accumulation in the parts above ground, which will then be harvested. Plants with a wide and dense root system should be favoured, as they have a greater absorption capacity and explore a larger area of soil.

Phytodegradation and phytosequestration

After absorbing a contaminant, some plants are capable of degrading it. After being exposed to various xenobiotics, plants have had to develop detoxification systems. The enzymes involved are not specific to the pollutants present, they are enzymes from the plant's secondary metabolism. The enzymes transform the compound by reduction, oxidation or hydrolysis, creating one or several soluble endogenous compounds that are either stored in the vacuole, or incorporated in the lignin or in the other cell wall constituents, and thus become non-extractable. For a mechanism based on degradation by plants, it is preferable for plants to synthesise large quantities of degradation enzyme.

Rhizodegradation or biostimulation

In this case, the plants have an indirect effect on the pollutant. They act as an activator of microbial degradation. The rhizosphere (the area of the soil close to the roots) is an area with high microbial density and activity. Plants can modulate the geochemical environment of the rhizosphere, which provides conditions that are more suited to the growth of bacteria and fungi. Some organic compounds in root exudates (phenols, organic acids, alcohols, proteins) can be used as sources of carbon and nitrogen for the growth and survival of microorganisms. The activity of microorganisms is encouraged by the presence of plants that create an appropriate physicochemical environment, encouraging the microbial degradation of organic pollutants. In some cases this interaction between the plants and microorganisms makes it possible to limit the use of fertilisers during bioremediation, through plant waste and root exudates.

Phytostabilisation

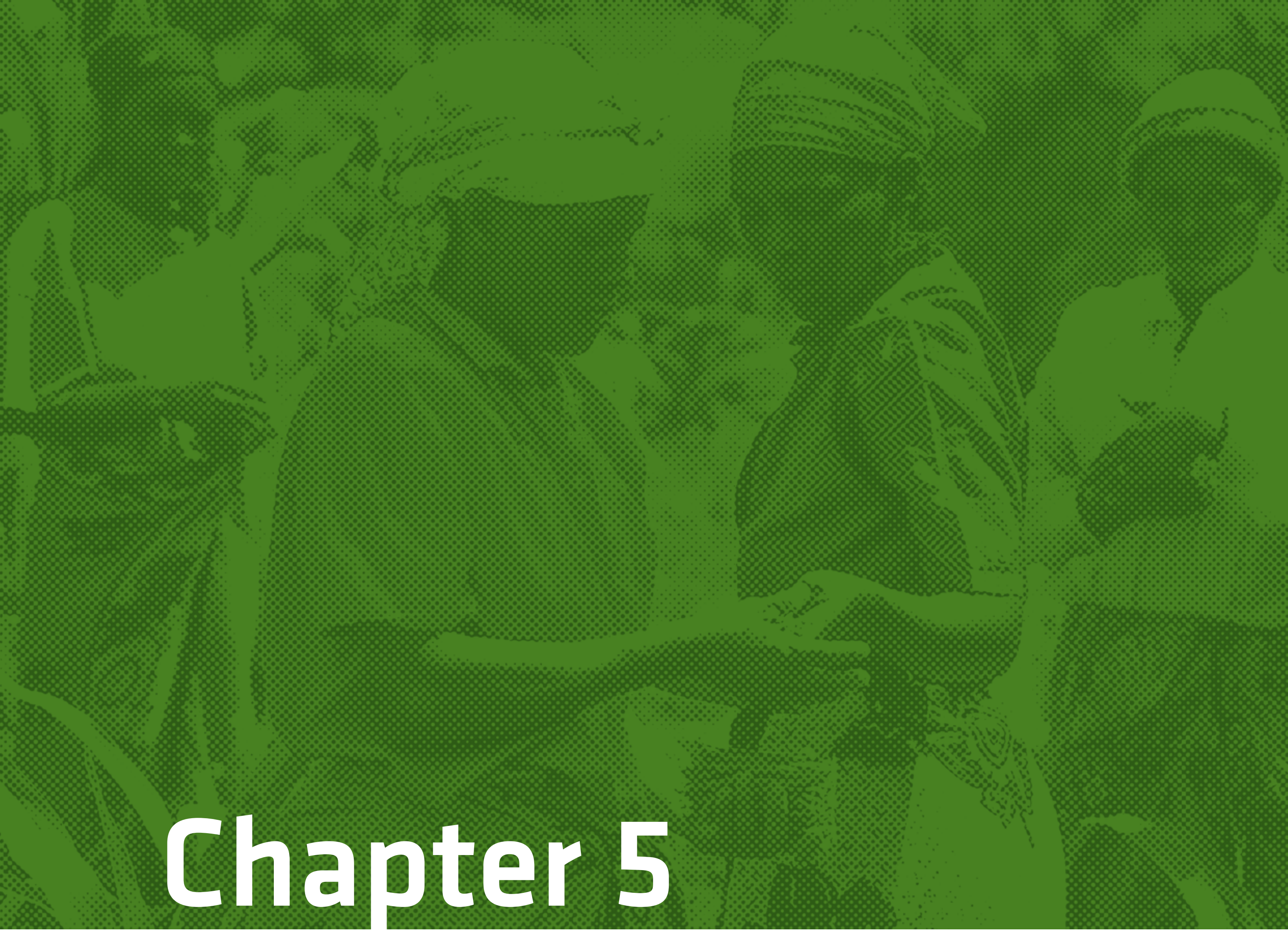
Some pollutants are resistant to the above mechanisms. In this case, phytostabilisation offers an alternative to the problem of controlling contamination. It is based on immobilising the pollutant in order to limit its dispersion in the environment and its bio-availability. It can consist of simple revegetation of the site, which prevents erosion and dispersion of the contaminant in the air and water. Plants can also be used as 'organic pumps' to absorb large volumes of water. Although the pollutant does not penetrate into the plant, it remains located in the initially polluted area; this does not reduce pollution in the soil, but it does reduce the migration of contaminants towards the water table. The plant roots also have the ability to modify environmental conditions such as pH or soil humidity. Some contaminants can be sensitive to these variations, and the presence of plants can therefore make it possible to reduce the bio-availability of the pollutant.

4.2.5.3. Soil decontamination through physical, chemical and thermal treatment

A few other treatments are theoretically possible:

- **physical treatments**: use fluids (water, gas) that are found in the soil or injected as a vector to transport pollution towards extraction points or to immobilise it
- **chemical treatments**: use chemical reactants to destroy the pollutants, and/or transport them into compounds that are less toxic and/or more easily biodegradable, or modify their characteristics
- **thermal treatments**: use heat to destroy the pollutant, isolate it or render it inert.

However, none of these treatments is completely effective in restoring the quality of agricultural soils.



Chapter 5

Case study

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LEARNING OUTCOMES

After reading this chapter, you will be able to:

- analyse a true-to-life scenario
- propose measurements or analyses to be conducted to make a diagnosis
- determine all the direct or indirect causes of a loss in soil fertility based on theoretical knowledge acquired
- propose a series of appropriate solutions to improve soil fertility in a sustainable way
- develop a coherent action plan to restore an acceptable level of fertility and sustainable soil management.

5.1. A CASE STUDY: WHY? HOW?

Working on the description of a hypothetical case will never replace your professional experience forged in the field and through contact with the everyday lives of farmers. However, from an example drawn from situations already encountered, it is possible to acquire **methodological principles** to analyse the situation and determine the nature and origin of problems that may be encountered by farmers; and to be able to propose **workable solutions** that are efficient, cost-effective and compatible with sustainability goals.

5.1.1. *How to use this case study ?*

A case study should not be used to propose a ready-made 'recipe' with ingredients that will always result in the same solutions to recommend to farmers. On the contrary, it should enable you to understand the **complexity** of situations that may exist and that require a **case-by-case** approach, with appropriate solutions suited to each situation and to the resources available locally. It must help the farmer to understand the **why** of their problems, and to determine themselves **how** a lasting improvement in the situation is possible, by weighing up the costs and benefits of each theoretical solution.

How can you use this case study to review the various aspects of sustainable management of soil fertility and apply what you have learned to a case that might be encountered in practice?

The case study has **four parts**, reflecting the four steps to be completed in the exercise:

1. **Scenario**: By reading the text, information can be identified that is relevant to understanding a situation that a horticultural business may encounter (in this case, concerning soil fertility). To refine the diagnosis, it may be necessary to propose measurements or analyses to be conducted.
2. **Situation analysis**: To identify causes and propose solutions for the business, the data will need to be analysed and a link drawn between the practices described and the problems encountered (nature, origin, interaction between observations), and the deviation from the business's objectives will need to be measured.
3. **Identification of appropriate solutions**: This will involve carrying out an inventory of solutions that would be appropriate to address each problem, identified separately; then observing, for each solution, whether it is: (1) effective; (2) profitable; (3) accessible; (4) sustainable.
4. **Proposal of an action plan for the business**: This means drawing up an implementation strategy, incorporating the selected solutions, to improve the situation in a sustainable manner to maintain or improve soil fertility.

To fully benefit from this case study, you should **follow the guidelines** and perform each step as a personal exercise, referring to the theoretical aspects described in this *Soils Handbook*, and consulting the relevant websites and resources provided.

At each step, you will see instructions, then a solution. You will see the following message:

"Have you completed your part of the exercise? Well done! Now compare your results with the proposed solution, identify the differences, and try to see why your results differ from this proposal. But perhaps you have thought of a new and/or a better proposal? Write your analysis of the results, and your personal perception, in a few lines: this will help you to retrace the reasoning behind your strategy at the end of the exercise."

Tip before you start:
Print the pages of this chapter to make your work easier.

5.2. PART 1: BACKGROUND

Instructions:

Read carefully this account of the difficulties encountered by a horticultural business. Identify, in the situation described, the key elements that will help you to understand the nature of this business's problems and the probable causes.

If necessary, print this page to re-read it several times.

(Disclaimer: this is a fictional case; any resemblance to actual situations, people or business names is entirely coincidental.)

5.2.1. Case narrative

For more than 10 years now, following the death of his father, who was a vegetable farmer as was his grandfather before him, Dieudonné Shamba has been the manager of the family business FRUITVERTS sarl. It is a medium-sized business (around 15 ha) on the outskirts of a large town, near some villages where a good number of his vegetables are sold all year round. This business produces some of its products (mainly green beans and cherry tomatoes) on site, but it also works with several small-scale farmers nearby, who provide it with fruit (mangoes) and some vegetables (okra, cabbage, peppers, tomatoes, amaranth, etc.) throughout the year. In its packaging station, it sorts and packs products for regional and export markets. Some of the tomatoes bought from local producers are also processed on site (dried) and packaged. The business is barely 30 km away from its main local market (in town) and from the large port from where its premium products (mangoes, fine green beans and cherry tomatoes) are shipped to Europe.

At FRUITVERTS, there are two growing areas. The part of the farm (8 ha) that is furthest from the coastline has the highest soils, which are fairly flat and divided into large squares separated by irrigation ditches. Until now, the soils, although sandy-clay, were fertile enough to accommodate crops to be grown for export. Green beans for the French market are produced there (6 ha) between September and March/April, and cherry tomatoes (2 ha) for the Dutch market, with the same crops being grown on the same plots every year.

Figure 1 - Crops grown on uplands (beans and cherry tomatoes)

The other soils, which are sandier (around 7 ha), slope gently towards the coast. They are interspersed with ditches hollowed by erosion. As they were considered to be less fertile, various vegetable crops (especially tomatoes, peppers and okra) for neighbouring markets are grown on the slope. The crops are distributed in small areas of a few acres, formerly separated by hedgerows that have mostly now disappeared. The small beds occupy land from the top to the bottom of the slope, where a large pond serves as a reservoir of water to irrigate these crops. On the slope, Dieudonné has planted a few trees to contain the soil and provide some shade for his nurseries. As far back as he can remember, Dieudonné has always known this division of crops. The surrounding villages are spread out along the coastline on the main road towards the town. Each villager has a small orchard of mango trees and some square beds where vegetables (tomatoes, melons, aubergines, etc.), maize, sorghum and groundnuts are grown, depending on the season.

Figure 2 - Bed grown by a smallholder

For the past two or three years, Dieudonné has found, when looking at his accounts, that the income he generates from his farm has fallen sharply. However, the sale price has tended to rise in line with the expansion of the villages and the large town, where there is a high demand for fruit and vegetables. It is clear that, on the whole, it is his production that has fallen. His business has produced far fewer beans and cherry tomatoes (these are the crops where the yield has fallen the most). For the other vegetables (tomatoes, okra and peppers), the fall in production has not been as dramatic, but it does not achieve the levels seen in previous years, despite repeated purchases of fertilisers and plant protection products. Unfortunately, the smallholders have not been able to offset the shortfall in his yield, even though they have been encouraged by him to produce as much as possible by increasing their surface area, and even though they have received compound fertiliser and plant protection products.

To produce his green beans and cherry tomatoes, Dieudonné has carefully prepared his land with his tractor, ploughing to 30 to 40 cm to dig in weeds and residues from previous crops (including maize grown in the wet season). Dieudonné has not been sparing with inputs, either. He has not hesitated to increase the quantities of NPK fertiliser spread (100-100-300), in addition to the fresh manure he works in when ploughing. He is careful to treat his crops several times a season with plant protection products (insecticides, fungicides) in order to increase his yields. For the past two years, he has even applied selective herbicides (atrazine) to beans, tomatoes and even maize to keep his soil clean and limit competition from weeds. Finally, over the past five years he has also increased the inflow of irrigation water, so that the beans and tomatoes take full advantage of his fertilisers and plant protection treatments. He has therefore installed a larger pumping unit on the pond to be able to irrigate the green beans and tomatoes more frequently by filling the channels winding across his fields with water. Nothing works.

His plants are sometimes attacked by diseases (e.g. fusarium wilt) that are treated with fungicides, but generally the leaves of his beans and tomatoes tend to be very dark green. On the other hand, during periods of great heat they tend to wilt more quickly. Dieudonné uprooted a few plants, but he did not find any traces of gall nematodes or rot on the collar. He does not understand what's going on.

Dieudonné's efforts are clearly not paying off. He needs the help of a specialist. Can you help him?

- *On a sheet of paper, try to **sort and list the problems** described (without reading further).*
- *Make a list of **observations, analyses and actions** that would be required to offer a diagnosis.*

5.2.2. Analysis of the situation described

Have you completed your part of the exercise? Well done! Now compare your results with the proposed solution, identify the differences, and try to see why your results differ from this proposal. But perhaps you have thought of a new and/or a better proposal? Write your analysis of the results, and your personal perception, in a few lines: this will help you to retrace the reasoning behind your strategy at the end of the exercise.

Proposed solution

Key information from the account given

- The business has diversified its products and markets. It produces throughout the year.
- Production is down. This is also the case for the smallholders, where fertility has declined.
- The business has been around for a long time. The same crops succeed each other year after year, on the same plots, and farming practices do not change much.
- Diversity of crops on uplands is limited (green beans or tomatoes/maize).
- Rotation is short. But alternating green beans and tomatoes is viable (acceptable previous crops).
- Crop diversity is higher for the rest of the farm and for the smallholders.
- Leguminous plants encourage nitrogen fixation in soils.
- Production is declining steadily, and this cannot be attributed to abnormal parasite pressure. The use of pesticides is frequent due to the repetition of crops. It compensates for pressure from insects and diseases.

- Herbicide treatments are carried out (e.g. use of atrazine, selective in maize).
- The soils are mostly loose and light (sandy-clay on uplands and sandy elsewhere), which is favourable to the cultivation of beans and tomatoes, which prefer lighter soils.
- Shallow ploughing is carried out (tractor passes on the uplands) each year.
- Residues from crops and fresh manure are worked in when the land is being prepared, just prior to sowing/planting.
- Large quantities of water are added to the crops.
- Large quantities of fertilisers and pesticides are added to the crops.
- The business is pushing smallholders in the same direction.
- Sloping land is subject to water erosion.
- The hedgerows are gone, trees are rare.

Observations, analyses and measurements to suggest

- Create a soil profile over 50 cm.
- Observe the colour of the soil.
- Observe the presence of tunnels in the soil and of other soil fauna.
- Perform a soil analysis to establish the nutrient content.
- Measure the organic matter content.
- Measure the soil's pH.
- Measure the soil's electrical conductivity.

Results of analyses, measurements and observations

- Observations:
  - By creating a soil profile over 50 cm, the depth of the surface horizon (horizon A) is limited to 20–30 cm at most. A gap area is observed at around 30 cm (darker horizon above a much lighter horizon).
  - It is observed that the soil is brown, or even dark brown (colour due to the clay and organic matter present).
  - Very few tunnels can be observed in the soil, and few insects and few earthworms.
  - Residues from previous, poorly decomposed, crops are observed.
- Soil analysis (in mg/kg):

N	P (P_2O_5)	K (K_2O)	Ca (CaO)	Mg (MgO)
688	339	834	4,445	388

- Analysis of organic matter content (result: **OM = 4.60%**).
- Soil pH measurement (result: **pH_{water} = 8.8**).
- Electrical conductivity measurement (result: **EC = 3.56 dS/m**).

My supplementary analysis (free space):

5.3. PART 2: CASE ANALYSIS

5.3.1. Guidelines for case analysis

Instructions:

To help Dieudonné, the causes of his business's low productivity need to be analysed. Work with two tools: a table and a root-cause analysis diagram.

Begin by completing the ***table*** *(if necessary, add more rows and columns). Don't forget to use the results of the soil tests and measurements (pH, EC, OM).*

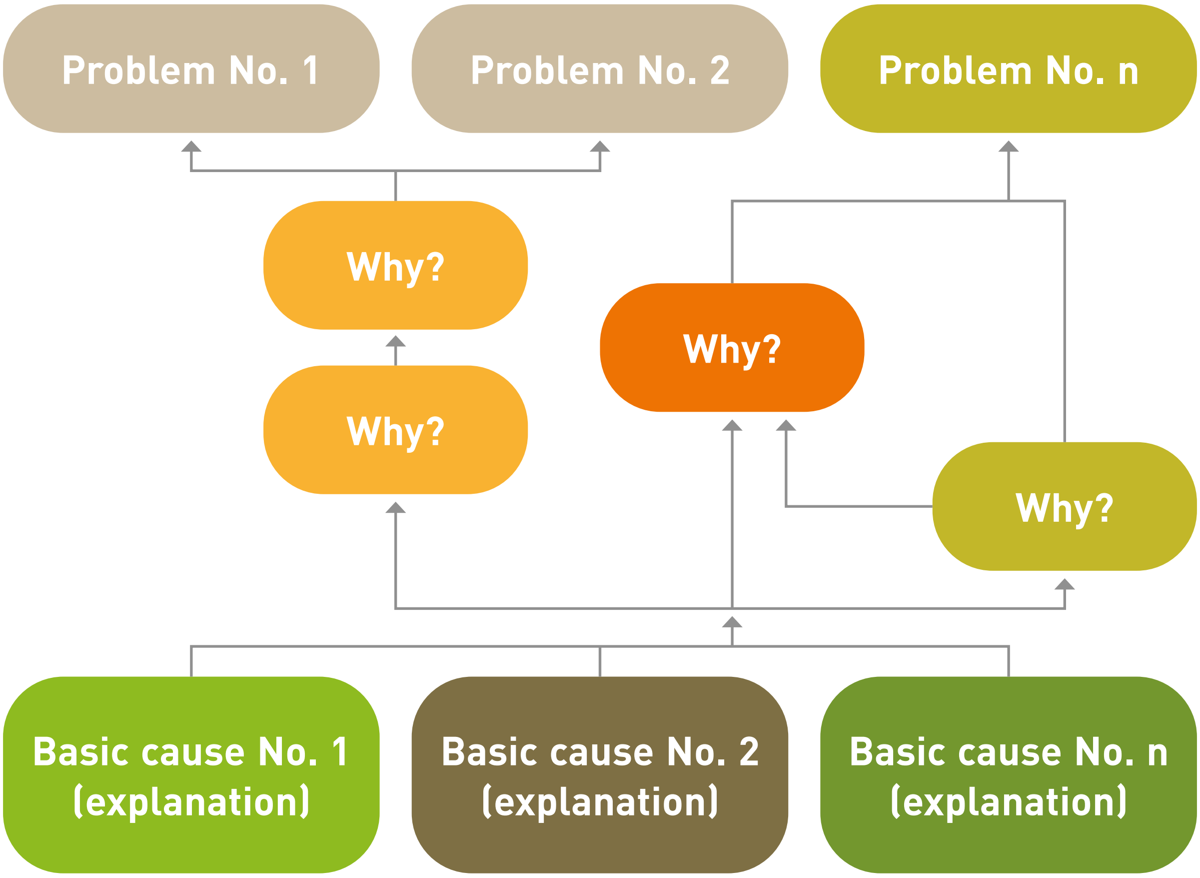
When the table is complete, create the ***root-cause analysis*** *in the form of a diagram (a flowchart, as shown in the example). Start by putting the problems identified in the boxes at the top and indicating the probable cause(s) in the boxes below.*

Table (example to print and complete)

Problem identified (finding, observation)	Tentative explanation	Identification of probable cause(s)

Root-cause analysis (example of a diagram to create and complete)

Begin with the findings (problems observed), then go back to the sources (sometimes multiple) that explain the origin of each problem. At the root there will be a number of deeper, more widespread causes.



5.3.2. Root-cause analysis: proposed result

Have you completed your part of the exercise? Well done! Now compare your results with the proposed solution, identify the differences, and try to see why your results differ from this proposal. But perhaps you have thought of a new and/or a better proposal? Write your analysis of the results, and your personal perception, in a few lines: this will help you to retrace the reasoning behind your strategy at the end of the exercise.

Proposed solution: table

Problems identified (finding, observation)	
The overall yield has declined, whereas previously it was satisfactory	
Tentative explanation	Identification of probable cause(s)
The soils were favourable to growing tomatoes, beans and other vegetables (light, loose, deep soils). Through his cropping and plant health practices, Dieudonné has made his soil less productive (a phenomenon called 'soil fatigue'), less resilient, less efficient at conserving water (soil structure has deteriorated despite the presence of organic matter and inputs of organic matter). Production by smallholders has not been able to offset the decline in the business's production, because fertility has also declined for them: this can be attributed to the same causes (misuse of inputs that have killed the soil life).	Repetition of the same crops on the same plots, with short rotation. Greater pressure from diseases and pests. Unsuitable fertiliser (excessive inputs, for example N and KCl), which does not compensate for exports due to successive harvests. Inappropriate irrigation (excessive inputs: asphyxiation; salt water – soil salinisation; dispersal of pathogens). Inappropriate cropping practices (manure not decomposed before sowing; ploughing that is too shallow; excessive use of inputs).

<table>
<tr><th colspan="2">Problems identified (finding, observation)</th></tr>
<tr><th colspan="2">Soil salinisation - EC = 3.56 dS/m) - Soil that is too rich in salts</th></tr>
<tr><th>Tentative explanation</th><th>Identification of probable cause(s)</th></tr>
<tr><td>At very low concentrations, some salts naturally present in soils are taken up by plants as nutrients. However, at higher concentrations soluble salts can inhibit plant roots' ability to absorb water and nutrients due to an increase in osmotic pressure, and thus restrict crop growth, resulting in lower yields. Some land-use practices contribute substantially to soil salinisation by altering the quantity and flow of water and salts through the root zone.

A high level of soil salinity has a toxic effect on plants. Beans, tomatoes and okra do not tolerate large inputs of KCl, which is not recommended for these two crops.

Check the COLEACP technical itineraries for green beans, cherry tomatoes and okra.

Beans are very sensitive to salinity (loss if EC >1 mS/cm).

Tomatoes tolerate it a little better (loss if EC >2.5 mS/cm), but are considered sensitive.

In tomatoes, KCl can cause an Mg deficiency (known as K/Mg antagonism).

The wilt observed is the manifestation of this salinisation.

Salt also affects the metabolism of soil organisms and leads to a significant reduction in the life, and therefore fertility, of the soil (cycles are slowed or even halted; e.g. humus is no longer formed).</td><td>Due to climate change (scarcity of rain), Dieudonné must irrigate his vegetable crops. The business practises corrugation irrigation, with heavy and increasing flows of water, but without ensuring sufficient and effective drainage (the water table is too close to the surface due to the geographical location).

Irrigation is one of the major causes of salinisation; the majority of irrigated soils have salinity problems.

When irrigation is too abundant to be absorbed by plant roots (absence of an effective drainage system), the soil is humidified deep down, allowing salt to rise to the surface.

The water is drawn from the pond that has formed at the bottom of the slope, near the shore. The salty groundwater table is raised to the freshwater surface after pumping.

The pond collects rainwater loaded with salts from fertilisers (e.g. large inputs of 300 units of highly soluble KCl).

Land clearing also causes salinisation. Unlike primitive vegetation, crops leave the soil bare at certain times of the year. Rains occurring at these times will not be absorbed and will cause the same phenomenon of diffusing salt to the surface.</td></tr>
</table>

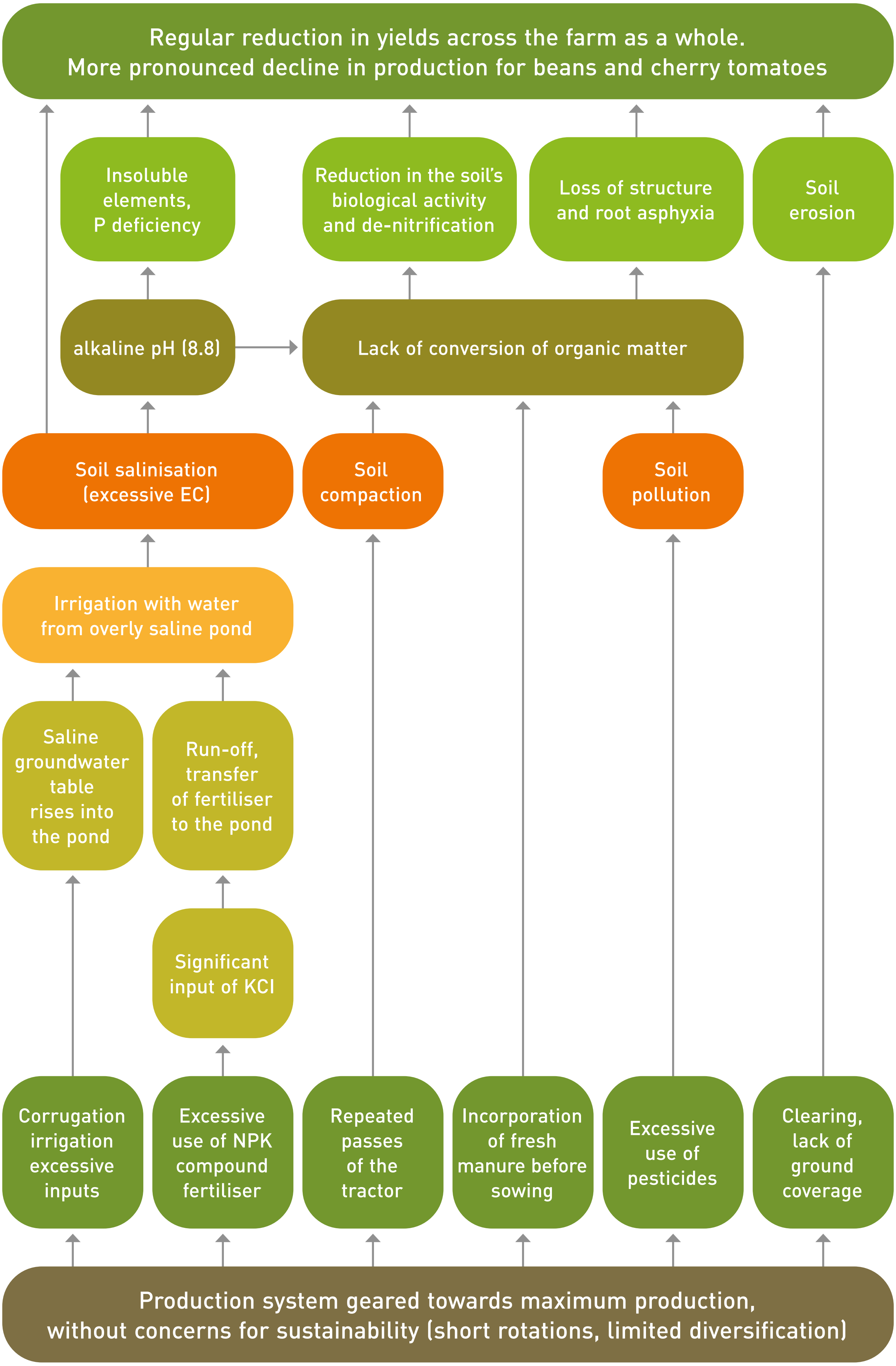
Problems identified (finding, observation)	
Soil compaction	
Tentative explanation	**Identification of probable cause(s)**
Settlement of the soil (tools but also the effect of excess fertiliser) Creation of a hardpan 40 cm deep due to repeated ploughing, whereas tomatoes require deep soil (at least 50 to 60 cm). Poor soil structure: despite the organic matter content (4.60%), the soil structure is unsatisfactory (soil that compacts, susceptible to erosion, lack of porosity). Excess sodium causes destruction of the soil structure, which, due to the lack of oxygen, becomes unable to support plant growth. Asphyxiating conditions for roots: bad for beans and tomatoes (sensitive to excess water). In tomatoes, root asphyxia causes Mg deficiency. Ridging of soil is necessary; roots need to be well ventilated and kept out of the water, however the cultivation is done on a flat soil with corrugation irrigation. Excessive water input exacerbates root asphyxiation in tomatoes. **Check the COLEACP technical itineraries for green beans, cherry tomatoes and okra.**	Repeated ploughing (tractor passes) at a depth that is too shallow. Loss of soil structure: negative effect of inputs on soil life and on the humification process; organic matter accumulates but no longer produces a viable humus. Soil with little porosity (poor circulation of air and water; negative effect on soil life, and progressive denitrification effect: despite the cultivation of a leguminous plant, the N content is abnormally low, <0.7 g/kg). The ‘anecic’ earthworms (those that aerate the soil) that allow water to dissipate are absent because of the toxic effect of pesticides. Salinity accentuates compaction by altering the soil structure.

Problems identified (finding, observation)	
Soil pH too high - pH_{water} = 8.8	
Tentative explanation	Identification of probable cause(s)
A pH >7.5 causes a gradual decline in yields in beans (optimum pH 6.1–7.4). When the pH is >7, this can cause an Mn deficiency in beans. The pH is too high for tomatoes (optimum pH 5.5–7.0). When the pH increases (pH >7), P availability reduces (seen in leaves of beans and tomatoes, which are dark green – a typical symptom of P deficiency). A lack of phosphorus also reduces the tomatoes' root system, which is already depleted by the presence of a hardpan.	Salinisation results in an increase in pH. When the pH increases, certain nutrients are less available (e.g. P or Mn) because they become insoluble, creating deficiencies, although soil analysis does not show any deficiency. Colouring of leaves is a symptom.

Problems identified (finding, observation)	
Poor management of organic matter	
Tentative explanation	Identification of probable cause(s)
Dieudonné adds organic matter (fresh manure), but ill-advisedly: incorporating organic fertilisers that have not fully decomposed into the soil before growing beans and tomatoes is strongly discouraged. Ploughing in crop residues before tomatoes is also not recommended. No fallow.	Pesticides disrupt the functioning of soil fauna and flora. Once disrupted, the flora and fauna cannot decompose the organic matter (mineralisation), leading to the loss of soil fertility.

Problems identified (finding, observation)	
Soil erosion	
Tentative explanation	**Identification of probable cause(s)**
The flat uplands that were productive in the past are no longer so, as Dieudonné has not considered wind erosion. His flat uplands are not protected by the shelterbelt and are therefore susceptible to wind erosion. In the absence of trees, shrubs and residues, which form a barrier to wind, the wind moves the soil particles over long distances, increasing soil abrasion and erosion. As mounds and hilltops are usually exposed, these are the places that suffer the most. The business's soils located on slopes are experiencing water erosion problems. On sloping land, the water runs off the soil surface. The run-off intensifies as the infiltration rate reduces due to soil compaction. In addition, the absence of earthworm tunnels in the soil reduces infiltration. When there is less fauna in the soil, there is also less excreta, and fewer binding and fining agents. Agglomerates tend to be more loosely linked.	Disappearance of hedgerows; only a few shade trees remain for the nurseries, which is insufficient. Erosion on the slope due to lack of soil structure (poor management of organic matter, compaction, salinisation, effect of inputs). Toxic effect of pesticides on soil flora and fauna: fewer earthworms, which reduces infiltration and increases run-off, encouraging erosion. Anecic earthworms allow water to dissipate. **Consult the various COLEACP training manuals on sustainable and responsible production.**
Problems identified (finding, observation)	
Soil pollution	
Tentative explanation	**Identification of probable cause(s)**
Phytotoxicity effect: residues from the atrazine used in maize and incorporated into the soil through ploughing are highly toxic to beans. Frequent use of pesticides in large quantities (increasingly because of poor rotations) kills soil life, interrupting the major biological cycles such as those of organic matter and nitrogen. Earthworms disappear.	The pesticides that Dieudonné has used to increase his yield are carried by the run-off water during precipitation and end up polluting soils and wells. Wells are very sensitive to contamination by pesticides, fertilisers, etc.

Proposed solution: root-cause analysis



My supplementary analysis (free space):

5.4. SEEKING APPROPRIATE SOLUTIONS

5.4.1. Guidelines for seeking solutions

Instructions:

To help Dieudonné, we must offer him appropriate solutions for addressing each problem identified. Work in two stages: briefly list the possible solutions to each of the problems in a table. Then check if these solutions are effective, profitable, accessible and sustainable (for each solution, evaluate these four criteria and give each one a score between 1 and 4).

Table 1 (example to complete)

Problems identified (finding, observation)	Proposed solution(s) (add some explanations)
Overall yield has fallen	S1: ....
Soil salinisation	S2: S3: ....
Soil compaction	S4: S5: S6: ....
Soil pH too high	S7: S8: ....
Poor management of organic matter	S9: S10: S11: ....
Soil erosion	S12: S13: ....
Soil pollution	S14: S15: S16: ....

Table 2 (example to complete)

Suggested solutions	Effective	Profitable	Affordable	Sustainable	Score
S1	4	2	3	4	13
S2	2	3	4	1	10
S3	4	4	1	2	11
S4	4	2	4	4	14
S5	...	...	...	...	...
S6	...	...	...	...	...
S...	...	...	...	...	...
Sn	...	...	...	...	...

(1: Poor; 2: Average; 3: Good; 4: Excellent)

5.4.2. Seeking appropriate solutions: proposed outcome

Have you completed your part of the exercise? Well done! Now compare your results with the proposed solution, identify the differences, and try to see why your results differ from this proposal. But perhaps you have thought of a new and/or a better proposal? Write your analysis of the results, and your personal perception, in a few lines: this will help you to retrace the reasoning behind your strategy at the end of the exercise.

Proposed solution: table

Problems identified (finding, observation)
Overall yield has fallen
Proposed solution(s)

S1: Review the current practices in full (rotation, tillage, input management, irrigation, etc.), adopt the principles of conservation agriculture and integrated fertiliser management for sustainable soil fertility.

Dieudonné must adopt good agricultural practices so that his business can produce a lot, as it did before. He must promote it to the smallholders with whom he works.

Careful soil management has always entailed using soils in ways that maintain, and if possible improve, their productivity. To do this, farming practices should not progressively alter the chemical and physical conditions of the soil, and should not reduce the soil's ability to grow plants when vegetable growing begins. It is normal for cultivation to lead to a degradation of the soils, due to the export of nutrients at the time of harvest, and physical damage to the soil structure. What is important is that this deterioration is reversible through good agricultural practices: judicious nutrient inputs, natural process of restoring fertility through the maintenance of life in the soil, observing good rotation, establishing hedgerows, trees and grasslands.

S2: Establish combination crops.

Establishing plant cover, consisting of a combination of species suited to the environmental conditions, and making use of perennial plants (shrubs, trees) offers a variety of benefits that can significantly improve crop productivity. It has been shown that multi-species agro-ecosystems (combination crops, mixing varieties or mixed planting) can increase productivity by 30 to 60% compared with single-species systems.

Agroforestry systems offer a large number of benefits for crop yields, such as improving the health of the agro-ecosystem, as well as sustainably maintaining a satisfactory level of fertility.

In addition, these systems encourage the development of mycorrhizal fungi. The key role of mycorrhiza lies in mobilisation for the plant of nutrients (mainly phosphorus) that are not very mobile in the soil. It would therefore be better to promote beneficial combinations while limiting the use of fungicides.

Establishing symbiosis also promotes the formation of aggregates and therefore improves the soil structure. Colonisation of the soil by the mycelium generates a better soil structure through the formation of much more stable aggregates.

Problems identified (finding, observation)
Soil salinisation
Proposed solution(s)

S3: Improve soils' water efficiency: better structure is needed (high-quality organic matter, agglomerates, porosity) to make them more resilient to prolonged drought periods and to keep cover on the soil.

By improving soils' water efficiency, the need for external water inputs, and therefore the risk of salinisation, is reduced. It is also important to avoid leaving soils without cover during periods of heavy rainfall (build-up of salts and soil erosion). By improving the quality of the organic matter in the soil, its capacity to store the water needed for plant nutrition is increased.

S4: Manage the irrigation water in a proper and rational manner: inputs need to be reduced by changing the mode of irrigation, which would make it possible to drain off excess water. It is therefore preferable for beans and cherry tomatoes to switch to a drip irrigation system. Elsewhere, reduce inputs.

Consult the COLEACP training handbook on sustainable water management for further information

Regular and precise monitoring of the water needs of various vegetable crops is required, based on the seasons and stages of these crops.

The pond water is loaded with salts. Where the irrigation water has little salt, surplus water can be added, but effective drainage must be ensured to allow the salt added by the irrigation water to dissipate with the drainage water.

However, in this case, there is a risk of increasing the level of saline groundwater, and contact between saline groundwater and the water used for irrigation. The groundwater would have to be drained while also limiting the inflow of irrigation water.

S5: Reduce salt intake: excessive inputs of NPK mineral fertilisers should be avoided, and KCl should not be used as a source of potash. Irrigation with saline water should be avoided (the salt content of good quality irrigation water is a maximum of 500 mg/litre).

Reducing salt inputs in the soil will allow soils to restore adequate biological activity.

Since KCl is harmful to beans and tomatoes, it must be replaced by another form of fertiliser compound (e.g. Patentkali®, which would also provide MgO, or NPK fertilisers). 300 units of potash is excessive; a maximum of 200 units would be sufficient. Don't forget that manure (or compost) also provides K_2O in significant quantity.

S6: Avoid clearing to expand cultivated areas: maintain cover and respect forest fallows.

Dieudonné should not routinely clear his land. A little-known consequence of this abrupt change in land use is an increase in water infiltration in slope soils caused by the decrease in evapotranspiration produced by the replacement of trees with seasonal plants. This disruption of the hydrological cycle can lead to an increase in saline water levels, and to the salinisation of vast areas of soil. To avoid this, it is important to retain vegetation.

In addition, consider establishing forest fallows that are able to draw up nutrients from deep down (from the alteration of minerals, from the recovery of solutions draining down beyond the roots of the crops) and recycle them on the soil surface.

Problems identified (finding, observation)
Soil compaction
Proposed solution(s)

S7: Avoid creating a hardpan: ploughing should be reduced (or even no longer practised) and deeper ploughing adopted instead (50 to 60 cm).

Ploughing that is too shallow has created a hardpan because the soil structure was poor and fragile. This hardpan must be broken down and then ploughing should be avoided when it is not useful. This will also avoid repeated passes of the tractor on the soil. For beans and tomatoes, it is not advisable to plough in crop residues, particularly fresh manure, before sowing or planting. The ploughing must be done well in advance to allow the manure time to decompose.

Dieudonné should consider managing the physical characteristics of his soil and should aim to preserve its structure or improve it using an appropriate mechanical preparation when the soil is not structured. Preparation of the soil is also important for combating weeds, which is often the main justification for ploughing and herbicide use. The techniques of minimal or no-soil preparation give good results. Damage to soil structure caused by ploughing can be avoided using these techniques (minimal or no preparation of the soil).

S8: Give the soil a good structure: it is necessary to have a well decomposed humus, good porosity, and a viable biological life. High-quality organic amendments must be used, in sufficient quantity.

The soil does not benefit from manure inputs as biological life is slowed and cycles are disrupted due to the toxic effects of excess chemical fertilisers, herbicides and other pesticides used. Care must be taken so that earthworms, insects and other animals can colonise the soil profile. Reduce fertilisers, and reduce irrigation to reduce salt inputs that destroy the structure and sterilise the soil.

Organic matter inputs are essential, but it is necessary to apply them in the right form (well decomposed organic matter) and at the right time in the rotation (ploughing in several months before cultivation). Integrated soil fertility management requires an organic matter–fertiliser combination for sustainable fertility.

The succession of plants from different families on the same plot is favourable to structure: thanks to the different roots, the soil profile is utilised better, which results in an improvement in the soil's physical characteristics, its structure (by limiting compaction), and therefore the plants' nutrition.

The formation of a surface-sealing crust should be avoided by working on well drained soil, limiting passes and grouping tools together (non-disruptive and suited to the soil type).

S9: For tomatoes, avoid root asphyxiation by creating ridges: tomatoes should be cultivated on ridging.

Problems identified (finding, observation)
Soil pH too high
Proposed solution(s)

S10: Reduce soil salinity: solutions S3 to S6 should be adopted.

The increase in pH is the indirect consequence of the gradual salinisation of the soils. We must therefore combat all causes that have led to this salinisation to return to a pH acceptable for tomatoes and phosphorus.

Attempting to acidify the soils artificially is not advisable (e.g. with the addition of certain fertilisers, since acidification would be even more difficult to control). Soils have a buffering capacity. In other words, they are highly resistant to pH variations. They often contain calcium and magnesium carbonates. These 'free carbonates' will react with acidifying soil improvers by neutralising them so that they prevent the pH from falling.

It is, however, possible to correct the pH by around one unit by adding elemental sulfur to the soil (350 kg/ha for a sandy soil, to be added several times a year). However, this can only work using bacteria that convert the sulfur into sulfate (SO_4^{2-}). It is this conversion that acidifies the soil.

The use of organic acid matter such as peat is also undesirable, because it is not very effective in amending the pH and is not compatible with environmental protection, since this material is extracted from ecologically fragile environments.

Improvement of the soil structure (through the repeated supply of well decomposed organic matter) will progressively correct the pH of the soil to bring it back to 7.

Problems identified (finding, observation)
Poor management of organic matter
Proposed solution(s)

S11: Provide well decomposed organic matter and incorporate it into the soil a long time before growing beans and tomatoes.

The direct addition of organic matter is necessary, but the organic matter should be provided in a well decomposed form (well rotted manure, compost); if not, it must be incorporated a sufficiently long time before cultivation, so that soil microorganisms can turn the fresh organic matter into humus.

The soil's organic matter plays a key role in nutrient retention. The organic matter + fertiliser combination is the basis for the principles of integrated soil fertility management. Organic matter also meets the nitrogen and sulfur needs of the vegetable crops.

Organic matter plays a role in stabilising the soil's aggregates and the survival of soil fauna at the origin of the pores (tunnels) through which air and water circulate.

Organic matter is the substrate for almost all of the soil's biological life. We know that soil contains living organisms that are of direct benefit to it, such as those used for nitrogen fixation and maintaining a favourable structure.

The soil's organic compounds prevent the formation of non-soluble iron and aluminium complexes associated with phosphorus, thus avoiding a decrease in the quantity of phosphorus available to plants.

S12: Establish an improved fallow system.

Rather than growing maize alone, after beans and tomatoes, Dieudonné should introduce it in combination with his Maize in association with cajan, or pigeon pea, a nitrogen-fixing legume in the soil. The introduction of pigeon pea (Cajanus cajan) into the maize does not entail additional ploughing. After harvesting the maize, the cajan stalks will be left in situ and will continue to grow until the pods reach maturity. The seeds will be harvested, and the leaves left on the soil for incorporation. Dieudonné will gain nitrogen for the maize and organic matter for the tomatoes and beans.

This technique should also be brought into general use among smallholders.

Problems identified (finding, observation)
Soil erosion
Proposed solution(s)

S13: Combat erosion (wind and water): a vegetable crop system without soil preparation should be favoured, and plant cover maintained to protect the soil.

A major advantage of cropping systems with no or minimal soil preparation is that they can be used to leave crop residue cover on the soil to protect it from the direct impact of rain. This prevents the dispersal of aggregate materials and maintains the soil's infiltration capacity, which minimises run-off and the resulting erosion problems.

When there is a marked dry season, termites can destroy plant residues so that the soil is left exposed and vulnerable at the start of the rainy season. Other mulching materials must then be found (grasses or branches from trees on the edges of the business's field), or other methods, such as grass strips or contour bunds, should be used to prevent erosion. These can be simple earth bunds constructed to carry water to a grassy channel to prevent the formation of gullies as seen in the vegetable crop fields of the business.

In drier areas, plant cover is also important to protect the soil from wind erosion, particularly the uplands where Dieudonné usually grows beans and cherry tomatoes. It is now recognised that maintaining plant cover on the soil is the key factor for its conservation.

S14: Keep and replant trees and hedgerows.

The trees have been uprooted or destroyed little by little (heavy felling). They need to be replaced. The hedgerows need to be restored. Trees, hedgerows and herbaceous barriers on the contour line slow down run-off, filter sediment material suspended in the water and encourage water infiltration. For example, Vetiveria zizanioides *(vetiver) is particularly suited to these functions.*

Trees and hedgerows also harbour populations of beneficial insects, birds, etc., useful for crop protection and to encourage the presence of pollinators, which improves productivity.

Problems identified (finding, observation)
Soil pollution
Proposed solution(s)

S15: Reduce the use of pesticides: the principles of integrated pest management should be adopted, and the number of treatments reduced.

Insecticides, fungicides and herbicides have noxious effects on soil microbes and organisms, and pollute water used for irrigation. This is especially true in this case as the groundwater table is close to the surface and the soil is quite sandy. In addition, the residues from herbicides applied to the surface should not be ploughed into the soil, because they are toxic to the crop that follows.

Dieudonné should keep to the recommended doses (limit excess doses). He must be able to reduce the use of pesticides by implementing the principles of integrated agriculture, such as crop rotation and mixing vegetable crop varieties. Rotation limits diseases and decreases nitrogen input; and it helps to break the life cycle of crop pests, weeds, etc. The succession of plants from different families on the same plot, for example alternating so-called 'cleaning' crops with leafy plants (e.g. Chinese cabbage), can break the cycle of certain species of weeds.

S16: Reduce the use of compound fertilisers: these are used excessively and, in addition, can introduce heavy metals into the soil (e.g. Cd). They should be replaced by organic fertilising material, which is less polluting, wherever possible.

One strategy to limit soil pollution from fertilisers is the application of fertilising material at the right time, in order to increase their effectiveness: before applying the fertilising material, Dieudonné should know the planting calendar and the composition of the soil (soil analysis). It is, for example, the composition of the soil that will determine whether Dieudonné needs to input more nutrients into his vegetable crop soils. He should know that it is not advisable to fertilise his vegetable crops during the rainy season.

Proposed solution: analysis of the solutions

Suggested solutions		Effective	Profitable	Affordable	Sustainable	Total score
S1:	Review the current practices in full (rotation, tillage, input management, irrigation etc.), adopt the principles of conservation agriculture and integrated fertiliser management.	4	4	2	4	14
S2:	Establish combination crops.	3	2	3	4	12
S3:	Improve soils' water efficiency: obtain a better structure (high-quality organic matter, agglomerates, porosity) to make them more resilient to prolonged drought periods and keep cover on the soil.	2	3	2	3	10
S4:	Manage the irrigation water in a proper and rational manner: reduce inputs (for beans and cherry tomatoes, by switching to a drip irrigation system).	4	4	1	4	13
S5:	Reduce salt input: avoid excessive inputs of NPK mineral fertilisers; KCl should not be used as a source of potash. Avoid irrigating with salt water.	4	3	3	3	13
S6:	Avoid clearing to expand cultivated areas: maintain cover and observe forest fallows.	2	1	2	4	9
S7:	Avoid creating a hardpan: reduce ploughing (or stop doing it completely) and instead adopt deeper ploughing (50–60 cm).	4	3	1	1	9
S8:	Give the soil a good structure: obtain a well decomposed humus, good porosity, a viable biological life. Use high-quality organic amendments, in sufficient quantity.	3	3	2	4	12
S9:	For tomatoes, avoid root asphyxiation by creating ridges.	4	4	2	2	12
S10:	Reduce soil salinity	4	3	2	4	13
S11:	Provide well decomposed organic matter and incorporate it into the soil a long time before growing beans and tomatoes.	4	4	3	4	15
S12:	Establish an improved fallow system (maize and pigeon pea).	4	3	3	4	14
S13:	Combat erosion (water and wind): adopt a vegetable crop system without soil preparation, and maintain plant cover to protect the soil.	3	2	3	4	12
S14:	Keep and replant trees and hedgerows.	3	2	2	4	11
S15:	Reduce the use of pesticides: adopt the principles of integrated pest management, and reduce the number of treatments.	3	2	2	4	11
S16:	Reduce the use of compound fertilisers, and replace them with organic fertilising material wherever possible.	3	2	3	4	12

(1: Poor; 2: Average; 3: Good; 4: Excellent)

Based on the scores, four priority areas stand out:

- Priority 1: S1 - S4 - S5 - S10 - S11 - S12 (scores of 13 to 15)
- Priority 2: S2 - S8 - S9 - S13 - S16 (scores of 12)
- Priority 3: S3 - S14 - S15 (scores of 10 to 11)
- Priority 4: S6 - S7 (scores of 9)

My supplementary analysis (free tables to complete):
other problems identified and/or other suggested solutions

Problems identified (finding, observation)	Proposed solution(s) (add some explanations)
....	S... : ....
....	S... : S... : ....
....	S... : S... : ....
....	S... : S... : ....

Other suggested solutions		Effective	Profitable	Affordable	Sustainable	Score
S... :						
S... :						
S... :						
S... :						

(1: Poor; 2: Average; 3: Good; 4: Excellent)

Classify all of your solutions based on a score that enables you to identify the actions that would be a priority to implement. It is most important for interventions to be consistent and strategic. Some steps should precede others.

5.5. ACTION PLAN PROPOSED

5.5.1. Guidelines for presenting an action plan

Instructions:

To help Dieudonné, propose an action plan for implementing the solutions, starting with those considered to be priorities. Work with a diagram (like the example) to indicate the strategy for implementing the interventions.

Action plan diagram (example diagram to use)

Indicate in the diagram the *N* steps to follow (general description of the objective) and the *N* actions to be carried out in each stage (based on the solutions considered to be priorities). In this example diagram, four steps are used:

STEP 1 :		
....	....	....

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STEP 2 :		
....	....	....

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STEP 3 :		
....	....	....

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STEP 4 :		
....	....	....

Create your own diagram and propose a full action plan. Then review the proposed solutions and compare them with your diagram.

5.5.2. Preparation of an action plan: proposed result

Have you completed your part of the exercise? Well done! Now compare your results with the proposed solution, identify the differences, and try to see why your results differ from this proposal. But perhaps you have thought of a new and/or a better proposal? Write your analysis of the results, and your personal perception, in a few lines: this will help you to retrace the reasoning behind your strategy at the end of the exercise.

Proposed solution: proposing solutions

The action plan should be created taking into account the priorities identified; however, focusing on one element to achieve an effect can address another problem at the same time. Therefore, if we focus on the priorities of the proposed solution:

- Priority 1: S1 - S4 - S5 - S10 - S11 - S12 (scores of 13 to 15)
- Priority 2: S2 - S8 - S9 - S13 - S16 (scores of 12)
- Priority 3: S3 - S14 - S15 (scores of 10 to 11)
- Priority 4: S6 - S7 (scores of 9)

STEP 1: **ANALYSE THE SYSTEM OF PRODUCTION AND THE MANAGEMENT OF INPUTS** Review the current practices in full, incorporate the solutions, trying to adopt the principles of conservation agriculture and integrated fertiliser management (IFM) This step is a prerequisite for determining the possible choices and future actions. The action plan will only produce results after several seasons.			
Review the cropping system (rotation and species)	Review the tillage	Review irrigation and water management	Review the management of inputs

STEP 2:
COMBAT THE SALINISATION OF SOILS

It is essential to prioritise this step, as the life of the soil, the change in pH and the soil structure depend on It must therefore be done before other interventions.

The effects will only be seen after several seasons.

Manage and reduce water inputs to crops	Avoid using pond water until its salinity is reduced	Replace KCl with another form of potash	Cease routine clearing, and no longer leave soils bare

STEP 3:
IMPROVE MANGEMENT OF ORGANIC

The management of organic matter needs to be changed, so that soils are enriched with humus, crops can take advantage of fertilising material, good cover is retained on the soil, a good structure is restored and erosion is combated.

The effects will only be seen after several seasons.

well decomposed organic matter: compost manure before using it; incorporate the manure long before sowing or planting	Establish improved fallow on an inter-seasonal basis: combine the maize habitually cultivated with pigeon pea

STEP 4:
RESTORE THE SOIL'S BIOLOGICAL QUALITY BY IMPROVING ITS STRUCTURE

In addition to changing the management of organic matter, there must be long-term action on the soil structure.

This step aims to obtain a quality humus by restoring biological cycles, for example reducing the denitrification by anaerobic bacteria (improved soil life). This will allow the soil to return to a good structure with sufficient porosity (the soil will be more water-efficient).

Avoid asphyxiating conditions: porosity will facilitate the circulation of air and the infiltration of water.

Establish combination crops (difference between roots)	Reduce tillage, avoid hardpans, avoid asphyxiating conditions	Replace NPK fertilisers with organic fertilising material as much as possible	With tomato crops, create ridges to avoid asphyxiation

STEP 5: COMBAT SOIL EROSION It is essential to combat wind and water erosion on all soils, but this requires first having restored a good structure to the soils. *Smallholders need to be made aware of good practices (avoiding the destruction of trees and hedgerows, adding shelterbelts, stone contours, bunds, etc.).* *The effects will only be seen after several seasons.*			
Reduce ploughing, do not destroy surface litter	Maintain plant cover on the rotation for as long as possible	Keep or replant the trees and hedgerows, especially on slopes	Cease routine clearing, and no longer leave soils bare

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STEP 6: ADOPT INTEGRATED INPUT MANAGEMENT Using inputs (primarily plant protection products and fertilisers) requires observations in the field (determining intervention thresholds), soil and leaf analyses (evaluating crop needs), and record-keeping (traceability). The negative impacts of chemicals toxic to the environment, and pollutants, need to be reduced	
Reduce the use of pesticides by adopting integrated pest management (prioritising crop control, resistant varieties, biopesticides, biological control, etc.)	Reducing the use of chemical fertilisers (reducing compound fertilisers) by regularly testing soils to adapt fertiliser application to needs

My supplementary analysis (free space):

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Glossary

GLOSSARY

Algae	Living beings capable of oxygenic photosynthesis, whose life cycle generally takes place in an aquatic environment. They are a very important part of biodiversity and provide provide the main base for freshwater, brackish and marine water food chains.
Associated crop	Associated cropping is a cropping system that involves cultivating several plant species or varieties on the same plot at the same time.
Bacteria	Refers to certain microscopic and prokaryotic living organisms present in all environments. Most often unicellular, they are sometimes multicellular (usually filamentous) and can also form colonies whose cells remain agglutinated within a mucous gel (biofilm).
Bedrock	In soil science, the bedrock is the superficial mineral layer of the earth's crust, whose weathering contributes to soil formation.
C:N ratio (carbon to nitrogen ratio)	Index that determines the degree of evolution of organic matter, i.e. its ability to decompose more or less rapidly in the soil.
Cation exchange capacity (CEC)	Corresponds to the sum of cations (positively charged atoms) that the soil can exchange. Some cations are located on the surface of soil particles with negative charges. These cations can exchange their place with other cations. This is why they are called 'exchangeable cations'.
Chelation	a physicochemical process in which a complex is formed – the chelate – between a ligand, known as chelator (or chelating agent) and a complex cation, which is chelated
Clay	Refers to a natural rock material based on hydrated aluminium silicates and/or silicates of lamellar structure, generally resulting from the weathering of three-dimensional framework silicates, such as feldspars.
Clay–humus complex	Structure formed of clay and humus. Humus is the stable fraction of soil's organic matter, in that it has a high tolerance to mineralisation, but makes a greater contribution to soil structure.
Colloid	Suspension of one or more substances regularly dispersed in another substance, forming a system with two separate phases. In a fluid, it forms a homogeneous dispersion of particles whose dimensions range from a nanometre to a micrometre.
Compost	Organic residue or a mixture of organic residue and soil piled into heaps, watered and allowed to decompose. Mineral fertilisers are sometimes added. When it is largely formed of plant residue, compost is often referred to as 'artificial manure' or 'synthetic manure'.

Composting Aerobic biological process that converts and recycles organic matter (by-products from livestock rearing, biomass, domestic organic waste, etc.) into a stabilised, hygienic, soil-like product rich in humic compounds, compost.

Conservation agriculture Set of cultivation techniques designed to maintain and improve the agronomic potential of soils, while maintaining regular and efficient production from a technical and financial perspective. These techniques rely on three mainstays: the reduction or even elimination of soil tillage; crop rotations; the use of soil-improving cover, with seeding done directly through the cover if possible.

Contour line Line formed by joining points on the land surface located at the same altitude.

Crop residues Part of the biomass of the crops that remain when the productive part of the crop, such as seeds and tubers, has been removed.

Crop rotation (or rotational farming) Alternation of crops on the same plot over the years. It is an important part of managing soil fertility and pests, and therefore beneficial for increasing yields.

Degraded soils Soils deficient in nutrients and with depleted organic matter, with low biological activity and poor structure.

Erosion The result of a process that begins with the disintegration of aggregates in the soil surface. It results in the formation of a structural then sedimentary crust, commonly known as surface sealing. This crust reduces water infiltration and leads to the formation of run-off.

Eutrophication Excessive growth of algae or aquatic plants due to the presence of high concentrations of phosphates and nitrates. The subsequent decomposition of the algae often leads to the depletion of oxygen, causing the death of other organisms.

Fallow period Period during which a field rests to restore soil fertility.

Farm manure Mixture of excrement and urine from farm animals, straw bedding and remnants from coarse fodder or from livestock fodder, having undergone partial decomposition.

Fauna Refers to all animal species present in a given ecosystem or geographical area (as opposed to flora).

Fertiliser Organic or mineral substances, often used as mixtures, designed to incorporate additional nutrients into plants to improve their growth and increase crop yield and quality. The act of adding fertiliser is called fertilisation.

Flocculation	Physicochemical process in which matter suspended in a liquid agglomerates to form larger, generally very porous, particles called flocs. Flocs generally sediment much more rapidly than the primary particles from which they are formed.
Flora	All plant species present in a given ecosystem or geographical area (as opposed to fauna).
Fulvic acids	Fraction of organic matter identified using chemical extraction processes. Substances not precipitated by acidification of the alkaline extracts from a soil sample, soluble in all pH
Fungi (singular: fungus)	This is a very broad term that covers living micro-organisms (mainly multicellular) such as moulds, rusts and yeasts.
General recommendations for applying fertilisers	Fixed recommendations for applying fertilisers that do not take into account variability in soils, climates and crop sequences.
Germplasm	A variety or seedling capable of responding to plant nutrients (varieties differ in their capacity to respond to nutrient input); adaptation to the local environment (soils, climate); and resistance to pests and diseases
Glomalin	Glomalin is a glycoprotein produced abundantly on hyphae and spores of arbuscular mycorrhizal (AM) fungi in soil and in roots
Gravel	Refers to somewhat coarse sand, most commonly used in river alluvial deposits.
Growth-limiting factors	Factors such as water and nutrients on the one hand, and livestock feed and food search time on the other, that limit the growth of crops and livestock respectively.
Half-moon	A farming method involving the digging of basins of a few metres wide into the land to form semi-circular pits (or mounds) in half-moon shapes, created using a pickaxe, mattock and shovel.
Humus	(i) the fraction of organic matter that remains in the soil after decomposition of most of the plant and animal residues incorporated into the soil. This matter is generally dark in colour. (ii) The term humus is also used in a broader sense to refer to the various types of forest humus layers, the main ones being mor (raw humus), moder and mull. See also soil organic matter, mor, moder, mull and soil horizon. (iii) Dead organic matter on the soil surface and in the soil undergoing a continuous process of decomposition, transformation and synthesis.

Humus	Upper layer of the soil created, maintained and changed by the decomposition of organic matter, mainly through the combined action of animals, bacteria and soil fungi.
Hypodermic transfer	Water running just under the soil surface. This is a horizontal movement, not a vertical movement like leaching; as it is not on the soil surface, it is not the same as runoff.
Infiltration	Refers to the process by which water penetrates the soil or other substrate from the soil surface or substrate.
Invasive weeds	Weeds that are particularly competitive with plants or which destroy them.
Ironstone	Hard crust and general term referring to a surface or higher horizon of a soil profile seen in semi-arid climates
Irrigation	Operation consisting of artificially introducing water into cultivated plants to increase production and facilitate their normal development, in the event of soil water deficit caused by a rainfall deficit, excessive drainage or lowering of the groundwater table, particularly in arid areas.
Labile	
Laterisation	The weathering process by which soils and rocks are depleted of soluble substances, such as silica-rich and alkaline components and enriched with insoluble substances, such as hydrated aluminum and iron oxides. Laterization is especially common in tropical regions that have a pronounced dry season and a water table that is close to the surface.
Latosols	Latosol is a name given to soils found under tropical rainforests with a relatively high content of iron and aluminium oxides.
Limestone	Sedimentary rocks such as sandstone and gypsum, easily soluble in water, composed mainly of calcium carbonate ($CaCO_3$), but also of magnesium carbonate ($MgCO_3$).
Liming	Application of an alkaline material (e.g. agricultural lime), such as dolomite limestone, to increase the soil's pH to the level required for plant growth.
Liquid manure	Liquid waste produced by domestic farm animals. It consists mainly of urine, possibly supplemented with liquid drained from a heap of manure.

Lixiviation	the loss of water-soluble nutrients from the soil, which are dissolved and carried away by infiltration water following rainfall or irrigation
Lixiviation	Movement of crop nutrients beyond the root zone, mainly due to excessive drainage in coarse textured soils.
Loess	Loose sedimentary rock, which is very porous and very permeable to water; its particles are less than 50 µm in diameter. Loess is a very fertile silt derived from wind erosion.
Macronutrients	Nutrients required by plants in large quantities (i.e. nutrients that make up at least 0.1% of the dry matter of plants).
Maerl	Collective name for non-geniculate coralline red algae with a certain growth habit (also known as rhodolith).
Marl	a sedimentary rock, a mixture of calcite ($CaCO_3$) and clay in roughly equivalent proportions, ranging from 35% to 65%. Beyond 65% calcareous content, it is a clayey limestone, while with less than 35% calcareous rock it is referred to as a limey clay
Metal trace element	The family of metal trace elements include the following elements: arsenic (As), cadmium (Cd), cobalt (Co), copper (Cu), chromium (Cr), mercury (Hg), nickel (Ni), lead (Pb) and zinc (Zn). They are often referred to as heavy metals, an imprecise term because some of these elements are not particularly heavy (zinc), and not all of these pollutants are metals, such as arsenic for example.
Microbial activity index	An enzymatic test to determine the potential degradation of the organic substrates of soil by certain enzymes, themselves produced by soil microorganisms. It shows the biological efficiency or the quality of the microbial biomass.
Mulch	A plant product that is spread on the soil at the bottom of the plants in order to enrich the soil as it decomposes. It also prevents weeds from growing and preserves the humidity level of the soil.
Mulch cropping	Cropping method in which organic debris is not incorporated or mixed into the soil, but left on the soil surface to be used as mulch.
Nutrient deficiency	Nutrient demand is greater than what is supplied by the soil, resulting in a reduction or disruption in plant growth.

Nutrient depletion	The export of nutrients by plant products and biomass is greater than the regeneration resulting from the addition of crop residues, farm manure and fertiliser.
Nutrient toxicity	Supply of nutrients from the soil exceeds the plant's requirements, so that growth is disrupted rather than enhanced.
Optimise	Using a resource in the most effective or best way.
Organic matter	Heterogeneous mass consisting of straw bedding, crop residues, live roots, animals of various sizes, etc., but also of plant residue in the process of decomposing, and evolved matter not distinguishable to the naked eye (humus).
Pan layers	Highly compacted layers of soil, hardened or with a high clay content
Pesticides	Insecticides, rodenticides, fungicides and herbicides: chemical compounds with toxicological properties used by farms to control animals (insects, rodents) or plants (fungi, weeds) deemed harmful to plants.
PH (or H^+ potential)	'Acid' nature determined by proton concentration (proton = H^+). The more protons the environment contains, the lower the pH (which means the environment is acid).
Photosynthesis	Process by which plants use the sun's energy to create living matter from carbon dioxide in the air and from water in the soil.
Plough pan	Dense soil layer under the surface that is impermeable to water. Mainly formed by compaction following repeated ploughing with a mouldboard plough and/or heavy vehicle traffic.
Polycondensation	Humic acids, which are reactives, can be bounded or associated with smaller molecules to form larger polymers, big molecules that are much more stable.
Primary factor	The most influential factor in determining the outcome of a given process.
Retrogradation	Retrogradation is linked to the pH and calcium content. When an input is added (e.g. liming), phosphorus can pass from a soluble to a solid state, unavailable to the plant. This phenomenon of retrogradation depends on various factors, and is more significant in calcareous or acidic soils. The phenomenon intensifies with high temperatures and low organic matter content.

Rhizobia Bacteria present in soil that form root nodules with compatible leguminous plants and which are capable of fixing atmospheric nitrogen (N) in the nodules.

Rotational farming (see crop rotation)

Run-off Phenomenon of water running off the soil surface. The opposite of the phenomenon of infiltration. This phenomenon occurs when the intensity of precipitation exceeds infiltration and the retention capacity of the soil surface.

Saltation Refers to irregular bouncing movements from one point to another. This is the process of transporting sediment by water or by wind. Driven by fluid, the particles (the size of sand or gravel) move in bounces.

Sand Granular material consisting of small particles resulting from the disintegration of other rocks, with a diameter range from 0.063 (silt) to 2 mm (gravel).

Sandstone Detrital sedimentary rock resulting from aggregation and cementation (or diagenesis) of sand grains.

Sedimentation A process in which particles of any matter gradually cease moving and settle together in layers. The factors causing sedimentation may vary in number and proportion.

Silt Sedimentary formation whose grains are intermediate in size, between clays and sands.

Slash-and-burn A farming method in which fields are cleared by fire, enabling a transfer of fertility, then cultivated for a brief period before being put into long-rotation fallow land, usually forest (forest fallow). This itinerant or extensive agriculture can lead to long-term soil degradation.

Slurry Agricultural effluent, mixture of livestock excrement (urine, faeces) and water, in which the liquid element dominates. It may also contain residue from livestock bedding (straw) in small quantities.

Soil acidification Phenomenon relating to the elimination of alkaline exchangeable cations and alkaline-earths (mainly Ca^{2+} and Mg^{2+}) in one or more horizons and which results in a reduction in pH. In adsorption complexes, Ca^{2+} and Mg^{2+} are gradually replaced by Al^{3+} and H^+. The acidification results from losses through lixiviation and export by crops.

Soil acidity A concentration of ions (H^+) in the soil. Acid soils have a pH of less than 7.

Soil buffering capacity A soil's buffering capacity plays a role in the stabilisation of the soil's pH, i.e. its acidity. Depending on their composition and mineral nature, more basic soils may react to changes in pH by neutralising acidity. This chemical reaction is called 'buffer effect'. A calcareous soil contains a good proportion of calcium carbonate (basic mineral). It is therefore able to chemically neutralise acids. Variations in pH in this soil type will therefore be less significant.

Soil climax Natural profile of the soil obtained (after a long period) in equilibrium with the climate, providing stable vegetation (e.g. forest), not modified by mankind

Soil creep Slow movement of surface soil particles downhill.

Soil health Physical, chemical and biological fertility of the soils.

Soil improver Material added to a soil to improve its agricultural quality. Improvers are therefore used in agriculture and gardening to improve land and make it more productive. One of the best-known improvers is lime, used to reduce soil acidity.

Soil porosity The amount of space filled with air and water between soil particles.

Soil profile All horizons of a given soil; each horizon being a layer detectable and distinct from that soil.

Soil structure Refers to the way in which the constituents of a soil are assembled, at a given moment in time. Structure, unlike texture, which does not change, is a state that evolves over time.

Soil texture Refers to the size and proportion of the mineral particles that make up the soil. More specifically, it refers to the proportion of sand, silt and clay contained in the soil. Sand is the largest of these three particles.

Splash effect Refers to the erosion of bare soil caused by the impact of drops of water. Even in the absence of runoff, splash may cause the creeping of sedimentary particles.

Stone Any small rock, usually quite hard, that may have been shaped by glaciers (polished, striated stone), wind (faceted stone), or water (pebble). Fragment of rock crystal, etc., that can be polished.

Strip cropping A cropping technique that follows different types of cultivation methods, such as line cropping and grassing in alternate strips along the contour lines, or perpendicular to the direction of the prevailing wind.

Surface sealing Character of a soil that tends to break down and form a crust on the surface due to the action of raindrops. This is one of the expressions of soil degradation.

Symbiosis Interaction between two different organisms living in close physical association from which both benefit.

Terraces Terraced cropping consists of cultivating on terraced or horizontal staggered platforms supported by stone walls or banks.

Trace elements Nutrients required by plants in small quantities (i.e. nutrients that make up less than 0.1% of the dry matter of the plant), which are often sufficient in most soils.

Upstream Source of a watercourse; its upper part, as opposed to the lower part, which is called downstream.

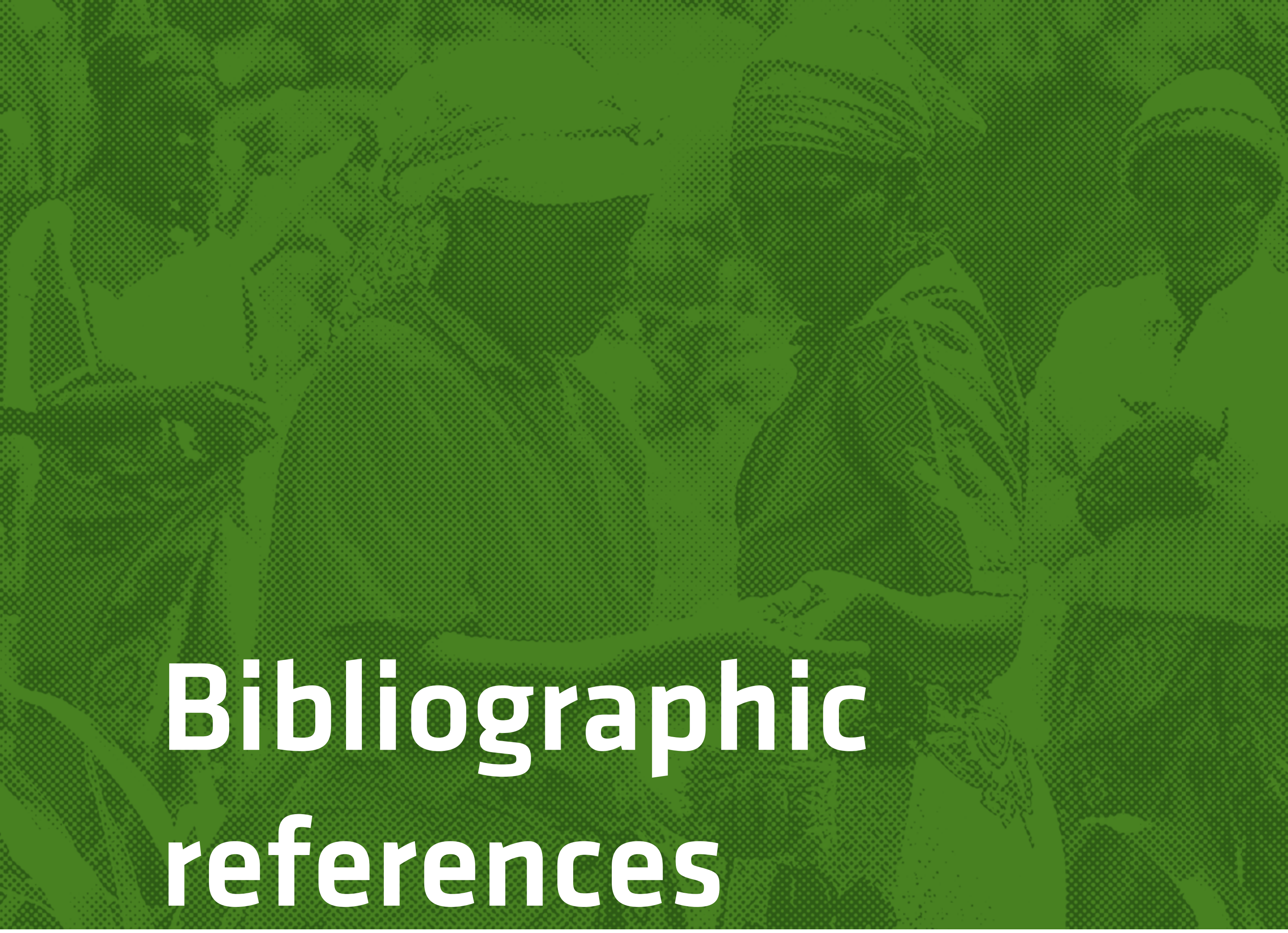
Watershed Area drained by a watercourse and its tributaries. All of the waters that flow into this area converge towards the same exit point, called an outlet (watercourse, lake, sea, ocean, etc.)

Weathering Weathering is defined as the mechanical destruction of rock structure (of solid rock or of consolidated sediments in (or on) which the soil has developed), which then triggers chemical changes in its constituent minerals. In principle, there are two main types of weathering: physical and chemical. Often also referred to as biological weathering, but it is in fact a manifestation of mechanical and chemical actions.

Windbreak or shelterbelt Planting of trees, shrubs or other plants, generally perpendicular or almost perpendicular to the direction of the prevailing wind, where the aim is to protect the soil, crops, housing and roads from the effects of wind, such as wind erosion, sediment transport and the formation of snowdrifts.

Xenobiotic A chemical substance found within an organism that is not naturally produced or expected to be present within the organism. It can also cover substances that are present in much higher concentrations than are usual.

Zai method Traditional cultivation technique from West Africa (Mali, Niger, Burkina Faso), now mainly practised by the population of northern Burkina Faso (Yatenga).



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Useful Web sites

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AGRIDEA:
www.agridea.ch/

COMIFER:
www.comifer.asso.fr/

FAO, ''Le sel de la terre : un danger pour la production vivrière'', 2002,
www.fao.org/worldfoodsummit/french/newsroom/focus/focus1.htm.

FAO, Several pages to consult, such as:
www.fao.org/soils-portal/about/all-definitions/en/
www.fao.org/conservation-agriculture/en/

GNB, Other literature on phosphorus:
www2.gnb.ca/content/gnb/en/departments/10/agriculture/content/land_and_environment/environmental_sustainability/phosphorus.html

Nice University: Several pages online about soil, such as:
unt.unice.fr/uoh/degsol/formation-sol.php
unt.unice.fr/uoh/degsol/strategies-techniques.php
unt.unice.fr/uoh/degsol/formation-sol.php#vegetation

OMAFRA, Other online courses (on erosion):
www.omafra.gov.on.ca/english/engineer/facts/12-053.htm

SVT, Description of a soil (definition):
www.vivelessvt.com/lycee/le-sol-2/

SUELOS, Soil horizon:
www.suelosdearagon.com/userfiles/images/perfil.jpg

SOS2, Restauration of soil fertility:
www.alliance21.org/2003/article918.html

SVT, Nutrition des végétaux:
soutien67.free.fr/svt/vegetaux/nutrition.htm

ULAVAL, Nitrogen sources in the soil:
theses.ulaval.ca/archimede/fichiers/20487/ch02.html

UP, Other literature on soil erosion:
www.u-picardie.fr/beauchamp/mst/Erosion_sol/Erosion-sol.htm

UNIVERSALIS, Other literature on (mineral) plant nutrition:
www.universalis.fr/encyclopedie/absorption-vegetale/

World Bank:
www.banquemondiale.org/

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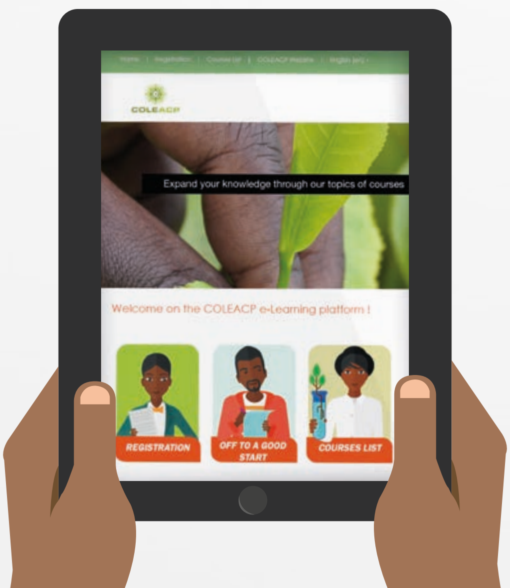

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