TRAINING NOTEBOOK

- ENVIRONMENTAL MANAGEMENT -

SUSTAINABLE SOIL MANAGEMENT

COLEACP

SUSTAINABLE SOIL MANAGEMENT

Dear trainers, some advice…

WHY A TRAINING NOTEBOOK?

The "Manuals" edited by COLEACP are valuable training materials. To write them, COLEACP approached the best experts in the field with the aim of producing a technical document for a large public on a given theme that brings together and structures most of the current knowledge. These manuals are intended to be as accurate and complete as possible, adapted to the ACP context and focused on cross-cutting issues in horticulture. But the objective was also to make them affordable, understandable and enjoyable to read by people who are not necessarily experts in the field. Nevertheless, it is a considerable effort to assimilate all the material collected in a short time.

The training manuals, which are aimed primarily at experts and the most qualified people, are often voluminous and complex, and it was necessary to help the expert trainers to identify the most important elements to retain, and to collect for them a list of 'key messages' to be disseminated to learners during COLEACP training. This Training Notebook is therefore a valuable and practical tool that is at your disposal to help you prepare your training on the topic covered in this Booklet.

WHAT DOES THE TRAINING NOTEBOOK CONTAIN?

Each Training Notebook contains:

1. The list of materials to be delivered to participants during the training

This is a summary table of contents of the Training Manual. This list allows you to have an **overview of** all the **main points that** will have to be covered during the training. The **order of the list does not necessarily have to be respected,** as the organisation of the sequences is left to your discretion and may depend on other factors (e.g. availability of an expert trainer; timing of the training sequences; space reserved for exercises...).

In some cases, **only certain aspects** (or chapters) of the **subject will be covered** (for example: if the participants have a perfect command of certain parts of the subject covered in the training, it is not necessary to present them in detail; a small reminder may be sufficient and effective to cover the rest).

However, when you cover part of the material (a chapter), the main 'points' listed for each chapter allow you to organise your presentations and animations in a logical and relevant way for the learner. **You are also advised to present all the points of a chapter.**

2. Training leaflets

A Training Notebook contains as many 'leaflets' as there are chapters in the training manual (only the 'case study' is not included). Each sheet contains, on the one hand, the **Training objectives** of this part of the subject to be delivered (what the learner must be able to deliver...), and on the other hand, according to the structure of the table, the 'key messages' (what the learner must absolutely have assimilated at the end of the training). It is therefore very important to ensure that **all messages are well distributed during the training sequence.**

3. A summary of the content of the manual

A summary of the manual has been included in this Training Notebook. Structured in the same way as the manual, it contains most of the content in 15-20 pages but remains much less complete (the summary does not include figures or case studies).

This summary is **primarily intended for the trainer.**

- **At the beginning of the mission**, when preparing its intervention sequences and supports, it allows you to quickly become familiar with all the content you will need to address and to visualise the links between the different parts of the material to be delivered.
- **During the training,** you can use this summary **to prepare your daily summaries,** reminding participants of the essential elements seen during a day (15-20 minute summary at the end of the day with answers to questions).
- **At the beginning or end of the training,** if you wish, you can give participants a copy of this summary. If the summary is distributed at the beginning of the training, it is advisable to ask participants to highlight the passages mentioned in your end-of-day summary (benchmarks in the subject).

The summary is also useful for learners at the end of the course: it will allow them to **remember in a** few minutes the **main part of the topic covered** (for example, before an assessment of prior learning), whereas reading the entire manual could be tedious.

HOW CAN THIS TRAINING NOTEBOOK HELP YOU PREPARE YOUR TRAINING INTERVENTIONS?

The intention of making this Training Notebook available to you is to **help you prepare your training sequences and structure your program day by day.**

- **Consider that each leaflet represents a whole:** if there are, for example, 4 leaflets, it means that there must be 4 distinct parts in your training. Sufficient time must therefore be allowed in the programme for each of these 4 parts. Each part of the subject will also have to be subject to a competency assessment.
- **Then consider the training objectives:** this will help you to choose: (a) the most appropriate training method for achieving your objectives (e.g. should you plan exercises, simulations, group activities etc.); (b) the method for evaluating the learning acquired in this part.
- **Finally, prepare your materials** (e.g. PowerPoint, flipcharts or animation sheets, evaluation questions) by ensuring that all key messages are included ("Have I planned to discuss all these points? Have I planned an evaluation on each key point?").

DON'T FORGET TO COMPLETE THIS TRAINING NOTEBOOK!

This Training Notebook is made **for you**... It is **a tool that must live!**

At the end of each leaflet, a space was left free to add your personal notes: as a trainer you can note some thoughts on how to get messages across, note your questions, participants' reactions, points that raise difficulties... *i.e.* **capitalise on your experience as a trainer!**

You can also **note the types of media you have used.** This will be very useful when you have a new session to facilitate on the same theme. COLEACP provides you with many tools and materials, but do not hesitate to create others or use other existing materials that may be available... the **rule is to master each of the materials used in training** and to ensure that they help to convey key messages more effectively than in their absence.

Materials to be delivered

CHAPTER 1 — FOUNDATIONS OF SOIL SCIENCE

- Introduction to Soil Science
- Soil formation and soil types
- Important soil properties
- The main functions of the soil

CHAPTER 2 — SOIL FERTILITY AND FERTILISATION

- Soil fertility
- How to assess fertility?
- Soil fertilisation and fertilising elements
- Role and nature of soil amendments
- Role of the aqueous phase of soils in fertility

CHAPTER 3 — CAUSES OF LAND DEGRADATION

- Soil degradation is mainly man-made
- Soil erosion
- Influence of farming practices on soil fertility
- The consequences of deforestation on soil
- The consequences of overgrazing
- Soil salinisation
- Soil compaction
- Soil pollution

CHAPTER 4 — PRESERVING AND RESTORING SOIL FERTILITY

- Preserve soil quality and fertility
- Restoring soil fertility

Training leaflets

LEAFLET 1

Foundations of soil science

TRAINING OBJECTIVES

At the end of this training sequence, the participant must be able to:

- understand what a soil is, what its composition is, what are its main fractions and major constituents;
- understand how soil is formed from bedrock and the factors that contribute to determining the characteristics of the soil formed;
- understanding the concept of 'soil profile';
- identify some representative soil types from different ACP regions and climates;
- identify the main soil properties (physical, chemical and biological);
- know the different functions of the soil;
- define the key elements and understand the objective of sustainable soil management.

KEY MESSAGES

1) Definition of the soil, its importance and composition

- Soil is the arable part where plants grow and develop.
- Soil is the interface between land, air and water and is the end product of the combined effect of climate, topography, and the activity of organisms on base materials over time.
- Soil is the farmer's main asset. It must allow for sustained and sustainable agricultural production.
- Soil fertility must be managed in an integrated way because it is difficult to lose and renew.
- Soil is a limited resource and takes a very long time to recover.
- Soil is a source of food, biomass and raw materials.
- Soil stores, filters and processes many substances, including water, nutrients and carbon.
- Soil is the world's largest carbon sink (1,500 gigatonnes)
- Soil consists of minerals (95%), water (15-35%), air (15-35%) organic matter (0-5%) and 3 phases (solid, liquid and gaseous).
- The solid phase of the soil is composed of mineral constituents (gravel and pebbles, sand, silt, clay) and organic constituents (living organic matter, fresh organic matter, transient organic matter, decomposed matter or humus).
- The liquid phase, or soil solution, is composed of water in which soluble substances from rock alteration, organic matter mineralization and human inputs are dissolved.

- The gas phase or soil atmosphere, or 'vapour phase', is composed of the same gases as air, with the addition of gases from the decomposition of organic matter.
- A soil is composed of superposed layers (horizons). This succession of layers is characteristic of a soil and its evolution.
- The understanding of the organisation of these various components is done by a vertical section of the soil, called a profile, which allows us to observe the different horizons resulting from geological, physical, chemical and biological processes (evolution according to local climate and weather).

2) Main mineral components of the soil and their roles

- The coarse elements (gravel, pebbles; sand and silt: diameter > 2 μm) forming the skeleton of the soil, constitute the mineral reserve of the soil.
- Coarse sands: they are sensitive to erosion but facilitate root penetration and temperature exchange.
- Fine silts and fine sands: they tend to settle under the effect of heavy rain that beats the soil and to form crusts on the top layer.
- Clay or clay minerals (diameters < 2 μm): they are present in the soil under various conditions (dispersed, aggregated or flocculated) which depend on the nature, the concentration and ionic strength.
- By associating with organic matter, fine clay particles participate in the formation of mixed colloids, the clay-humus complex (CHC).
- Mixed colloids are responsible for adsorption reactions that allow the binding of cations, anions or even charged molecules, such as pesticide residues and other soil contaminants.

3) The main organic constituents of the soil

- Soil organic matter comes from the death of living things, their waste and secretions.
- Vegetable substances account for almost all (99%) of the humus production.
- All soil organic matter includes fresh or slightly evolved organic matter and humic substances composed of organic macromolecules or 'colloids'. The advanced products are humic and fulvic acids.
- Humic acids: they are not very mobile, constitute a significant quantity of soil carbon with a binding power that plays a role in the stability of the CHC (clay-humus complex)
- Fulvic acids: they are more mobile and constitute most of the carbon dissolved in natural waters.
- Fulvic acids are the main leaching agents of iron and have the ability to chelate several minerals from the soil to promote their absorption by plants.
- Humus is in the superficial part of the soil, it is the final product resulting from the decomposition and transformation under the action of many biological agents present in the soil of these organic materials and substances.
- Humus improves soil structure, resistance to the erosive action of rain or wind.
- Humus improves the water storage capacity and retention of nutrients, nitrogen (N), phosphorus (P), potassium (K), and releases them slowly to plants over a longer period of time.

- Humidifying agents are: soil flora containing algae, bacteria, fungi and soil fauna consisting mainly of woodlice, ants, collembola, earthworms, slugs and myriapods.

4) Soil formation: process used in pedogenesis

- Soil formation involves several steps: alteration, organic matter enrichment, and finally migration of substances and particles into the soil profile.
- The bedrock disintegration and alteration allow the separation of grains from a coherent rock by the action of physical phenomena or by the chemical alteration of certain constituents.
- Alteration consists of two stages: the mechanical destruction of the rock structure, which will then facilitate chemical modifications of the minerals.
- Organic matter (OM) enrichment is possible thanks to the work of living organisms (especially burrowers).

5) Main factors that are fundamental to soil formation

- The composition of the bedrock: original material called parental material.
- Climatic conditions (temperate, subtropical, tropical): this is the driving force of change. Temperature and humidity are crucial to explain the evolution of a soil.
- Living organisms: vegetation on the surface and micro-organisms in the soil.
- Time: the duration of events, their succession.
- Topography and human interventions (type of crops, cultivation methods).

6) Most common representative soil types in ACP countries

- Desert soils: they are not suitable for cultivation because they are too poor.
- Brown soils: soils that provide the best agricultural land (and forest soil and climate).
- Ferruginous soils (in the grassy savannah soil climate) and fersiallitic soils: they are called ‘red soils’; they are very advanced because of the climate.
- Ferrallitic soils: fragile soils present in the conditions of a humid tropical climate.
- Saline and sodium soils: excessive concentrations of soluble salts.
- Hydromorphic soils in areas (lowlands) and wetlands.

7) Physical, physico-chemical and biological properties of soils

- Soil texture: this is the granulometric distribution of soil constituents.
- The soil texture makes it possible to assess the physical quality of the soil with 4 fundamental classes: sandy, silty, clayey or balanced texture.
- Soil structure: it is the way in which soil particles combine to form aggregates.
- There are 3 main types of structures: fragmentary, particulate or compact.
- The clay-humus complex (CHC) and cation exchange capacity (CEC): CHC is a structure formed of clay and humus; cation exchanges take place between CHC and soil solution: this represents CEC.
- Soil acidity (pH) and soil buffering capacity: acidity is defined as the concentration of H^+ ion in soil water and buffering capacity is involved in stabilising soil pH.

- The biological properties of soils depend on the presence and diversity of species: there are more than 4,000 bacterial genotypes and more than 2,000 species of saprophagous fungi in the soil for the decomposition and production of OM.
- The soil contains up to 1,000 species of invertebrates: molluscs, insects, diplopods or myriapods, earthworms (burrowing), mites, springtails, nematodes and protozoa.

8) Main soil functions

- The soil is a support for the production of plants in the recycling of nutrients.
- Soil participates in the cycles of nitrogen (N), phosphorus (P) and potassium (K), elements necessary for plant development.
- Soil is one of the carbon sinks. It participates in the carbon cycle by storing and releasing carbon into the atmosphere.
- Soils release atmospheric carbon (CO_2), which contributes to global climate regulation.
- Soil is a storage medium and allows the purification of infiltrating water.
- The soil is a reserve of biodiversity: a formidable factory to be transformed and created from living things because thousands of animal and plant species live in the soil.
- The soil is a place of life, rich in species and living beings: the many micro-organisms, invertebrates and bacteria form 80% of the biomass.
- In the soil, each species plays a role as a transformer of organic and mineral matter to make it usable by plants.
- Soil plays a role in regulating biological populations, particularly pests and diseases.

9) Definition of sustainable soil management

- Sustainable land management was defined by FAO in 2017 in the “Voluntary Guidelines for Sustainable Land Management” which specifies its characteristics.
- Soil management is sustainable when the services provided are maintained without compromising biodiversity or the functions that provide them (delicate balance between crop production services and regulatory functions on water quality and availability, and on greenhouse gas concentration).
- Characteristic 1: low water and wind erosion, and no degradation of soil structure (no compaction or settling of the soil).
- Characteristic 2: presence of sufficient vegetation cover, or plant residues, to protect the soil and ensure a stable or increasing supply of OM.
- Characteristic 3: availability and circulation of nutrients, adapted to maintain or improve soil fertility and productivity, reduction of losses.
- Characteristic 4: low salinisation, sodisation and alkalisation
- Feature 5: infiltration and storage of water from efficient rainfall (or irrigation): meet plant needs and ensure drainage of any excess water.
- Characteristic 6: contaminant concentration below toxicity levels that are hazardous to plants, animals, humans, the environment and soil biodiversity.
- Characteristic 7: optimised and safe use of inputs (pesticides, fertilisers, soil improvers).
- Characteristic 8: minimised soil sealing, responsible land use planning.

10) Interest of sustainable soil management

- Sustainable soil management is a response to the global challenges of global food security for an environmentally sustainable agriculture focused on soil conservation and the environment.
- Regulation (EC) No. 834/2007 on organic production requires soil management to maintain (or even improve) soil fertility.
- Regulation (EC) No. 834/2007 requires soil management to prevent soil erosion and compaction.
- Sustainable land management is the starting point for poverty eradication, agricultural and rural development.
- Sustainable land management is the starting point for promoting food security and improving nutrition.
- Sustainable soil management is a requirement of certain standards such as GLOBALG.A.P. or Fair Trade.

PERSONAL NOTES AND REFERENCES OF THE MATERIALS USED

LEAFLET 2

Soil fertility and fertilisation

TRAINING OBJECTIVES

At the end of this training sequence, the participant must be able to:

- understand the concepts of fertility, fertiliser and amendment;
- define the fertility of a soil, to know the elements that influence this fertility;
- know how to assess the fertility of a soil;
- understand the role of the main nutrients (N, P, K and others), their forms, sources and the risk of loss of these nutrients;
- identify the main soil amendments: nature and role of each type of amendment (limestone, magnesian, humus, organic);
- understand the role of the aqueous phase of the soil in the plant's absorption of fertilising elements.

KEY MESSAGES

1) Soil fertility requires its structure, nutrients and biology

- The fertility of a soil is its ability to support crop production. Fertile soil is a substrate that supports optimal plant growth, from seed germination to plant maturity.
- Fertiliser (organic or inorganic substance) contains nutrients in forms that can be assimilated by plants.
- Fertilisation is a process of providing a growing medium with the nutrients necessary for plant development.
- An amendment is a material made to a soil to improve or correct its agricultural quality (mainly to improve its structure).
- The nutrient balance is the difference between the amount of nutrients provided by organic matter and fertilisers, and the amount of nutrients exported by the crop or lost (leaching).

2) The physical factors that determine soil fertility

- Rainfall and temperature (climate) influence soil fertility.
- The depth, texture, soil structure and physico-chemical properties of the soil determine its fertility.

3) Importance of organic matter and soil biology for nutritional fertility

- Organic matter is essential for maintaining nutrient richness and soil water retention.
- Soil micro-organisms are involved in the physical and chemical aspects of soil quality and strongly influence soil fertility.

4) How to assess soil fertility

- Soil fertility is assessed on the basis of 4 main criteria and by different and complementary methods (observations, analyses, tests).
- Criterion 1: great depth.
- Criterion 2: a texture and structure with medium grains and a neutral pH (pH 6-7).
- Criterion 3: a mineralogical composition of the parental substrate giving either a homogeneous substrate poor in nutrients or a heterogeneous substrate (sandy-calcareous clay) but rich in various elements providing a balanced diet.
- Criterion 4: a reserve of major nutrients (N, P, K) and humus composition: colloids improve the structure of the soil and complexes that can be mobilised with mineral substances.
- The determination of soil fertility can be done by visual diagnosis according to colour: according to colour, clarity and purity (coding and comparison with coloured standards — Munsell code or charter.
- Soil fertility can be determined by indicator plants: the presence of a species has an informative value on the chemical quality and the degraded or undegraded state of the soil.
- Soil fertility can be determined by analysing plant tissues: tissue analysis gives indications of the nutritional quality of the soil.
- Soil fertility determination by laboratory soil analysis: complements field observations to better determine soil qualities and defects.
- The determination of soil fertility by the diagnosis of the structure and the biological activity of the soil by a soil profile: the ‘spade test’ with macropores counting.
- Soil fertility determination by counting and identifying earthworms.
- Soil fertility determination by measuring the time of water infiltration (assessing soil porosity).
- Soil fertility determination through good observation of the shape and density of plant roots.
- Soil fertility determination by microbial biomass analysis.

5) Soil fertilisation and fertilising elements

- Fertilisation must always be rational and meet the objectives of sustainability by integrating the economic and environmental context.
- Nutrient balance: it is necessary to determine the import-export of nutrients and to avoid soil depletion.
- Nutrient management: it is necessary to compensate for crop withdrawals and losses with refunds (fertiliser inputs or other methods).
- Major chemical elements are essential for plant nutrition: nitrogen, phosphorus and potassium (N, P, K).

- Secondary elements (calcium, magnesium and sulphur and trace elements, iron, zinc, manganese, copper, boron, molybdenum, chlorine and nickel) are also required.
- The reasoned and sustainable management of fertilisers is based on three fundamental laws: the law of restitution or advances; the law of less than proportional increases; and the law of the minimum or interaction.
- The principles of integrated soil fertility management (ISFM) are based on the combined use of fertilisers (essential to increase yields) and organic matter (to improve the efficiency of the fertilisers provided).
- The efficiency of fertilisation success factors depends on land use, cropping plan and cultural practices.
- The principles of ISFM are based on conservation processes, the use of organic matter and the system of fertiliser use or reasoned amendment.
- The optimal use of the main fertilising elements (N,P,K) by plants depends on their shapes, sources and the risk of loss of these elements.
- Mineral amendments provide calcium and magnesium.
- Organic amendments (or organic materials) are intended to maintain or enrich the soil humus stock.

6) Role of the aqueous phase of soils in soil fertility

- Soil water available to the plant or 'useful water' is the amount of water that the soil can absorb and return to the plant.
- Nutrients are only recovered by plants if they have enough water in the soil to absorb them.
- Water is both a food source of hydrogen and oxygen, and a vehicle that allows the roots to absorb fertilising elements.
- Water plays a role in the transfer of ions between the solid phase of the soil and its liquid phase: mineral elements, adsorbed on colloids, are dissolved and released into the soil solution where they pass to the root through two processes: mass flow and osmosis.

PERSONAL NOTES AND REFERENCES OF THE MATERIALS USED

LEAFLET 3

The causes of land degradation

TRAINING OBJECTIVES

At the end of this training sequence, the participant must be able to:

- understand why and how land degradation is primarily due to human activities, and the extent of the phenomenon;
- know the causes of the decline in soil fertility (modification of its physical and chemical properties);
- understand the phenomena of erosion, deforestation, salinisation, soil compaction;
- identify the nature and origin of the various soil pollutants and the danger they pose to humans, plants and the environment.

KEY MESSAGES

1) Land degradation is primarily due to human activities and the extent of the phenomenon is global

- The area of cultivable land is constantly decreasing, at a high rate of about 5 to 10 million ha per year.
- The rate of degradation of arable land is estimated at 25% in Africa, 38% in Asia, 21% in America, 11% in Europe and 5% in Oceania.
- Soil degradation and loss of fertility are an economic and ecological concern everywhere in the world.
- Land degradation is of greater concern where population growth is highest.
- Land degradation is aggravated by increased competition between different land uses.
- Competition between different land uses, supported by a lack of sustainable soil management, leads to a continuous degradation of soil properties and fertility.
- Soil is now a limiting factor in the supply of food, both in quantity and quality, and soil conservation policies in agriculture are essential.

2) The causes of the decline in soil fertility

- The decline in soil fertility (deterioration of the physical, chemical and biological properties of the soil) is largely directly related to human action.
- Erosion, lack of cover, loss of organic matter and compaction are the causes of deterioration of physical properties or soil structure.
- The deterioration of soil chemical properties results in salinisation, acidification and nutrient depletion.

- Deterioration is caused by pollution from industrial waste or by the excessive application of pesticides or chemical fertilisers.
- Soil acidification is a natural phenomenon caused by rain and certain biological processes.
- Soil acidification is exacerbated by the intensive use of chemical fertilisers.
- Soil pollution by heavy metals (or toxic materials) is caused by the addition of manure, slurry, compost from household waste and chemical fertilisers.
- Biological degradation can be explained by certain cultural practices, the contribution of chemicals toxic to soil organisms, the decrease in soil organic matter content, the low pH, the combustion of biomass and the depletion of vegetation cover.

3) Soil erosion

- Soil erosion is a natural or anthropogenic phenomenon that can have beneficial effects such as the deposition of alluvial deposits, but is generally harmful.
- Soil erosion is the stripping or process in which soil particles are removed, transported as well as deposited as soluble and solid elements of the soil under the influence of water (water erosion) or wind (wind erosion).
- Water erosion occurs in 3 stages: detachment, transport and sedimentation. The particles settle in the following order: sand -> fine sand -> silt.
- Wind erosion can occur anywhere if soil, climate and vegetation conditions are favourable. Loose, dry and finely crumbled soil, a sufficiently wide field and a sufficiently strong wind to initiate particle movement are favourable conditions for wind erosion.
- The rate and extent of erosion depends on the erodibility of the soil, the roughness of the soil surface and the climate.

4) Deforestation and overgrazing lead to land degradation

- Deforestation is increasing rapidly, especially in sub-Saharan Africa, where forests are being continuously destroyed. Every year, some 13 million hectares of forests disappear worldwide, and forests are home to 80% of the world's terrestrial biodiversity.
- Deforestation means depriving oneself of valuable ecosystem services.
- Deforestation in tropical areas is caused by the expansion of agriculture, timber extraction, charcoal or fire production, infrastructure expansion and mining.
- Deforestation leads to: land degradation, loss of biodiversity, climate change (massive release of CO_2), natural disasters, depletion of water resources and aggravation of certain diseases.
- After deforestation, the regeneration of natural vegetation takes a long time (about 20000 years).
- Overgrazing: pressure on grazing areas leads to a loss of edible vegetation and a dominance of shrub species, leading to desertification.

5) Soil salinisation

- Soil salinisation is a way in which soil productivity can be reduced without loss of soil cover.
- Salinisation results from the accumulation of water-soluble salts in the soil: potassium (K^+), magnesium (Mg^+), calcium (Ca^{++}), chloride (Cl^-), sulphate (SO_4^{++}), carbonate (CO_3^{++}), bicarbonate (HCO_3^-), and sodium (Na^+).
- Soil salinity results from the presence of dissolved major mineral solutions in water or soil.
- Soil salinisation is a progressive increase in the concentration of water-soluble salts in the soil solution under the influence of natural or anthropogenic factors.
- Salinisation is most often the result of irrigation of poorly drained soils in arid climates, and results in an accumulation of salts in the most superficial horizons.
- Salinisation is caused by agricultural practices or inappropriate developments, geological material, seawater or groundwater by geological heritage.
- Salinisation leads to a decrease in yields, or even soil sterilisation, variations in pH (up to 10) making many nutrients insoluble, thus reducing soil fertility.
- Salinisation reduces the microbial activity of the soil at the base of nitrification processes, promotes the increase of soluble organic compounds and the decrease of humic compounds.
- Soil salinity is assessed by ion analysis methods.
- The salinity tolerance threshold is specific to each plant species.

6) Compaction

- Compacted soils are more sensitive to erosion, contribute less to the purifying and 'buffering' functions of soils.
- Soil compaction is caused by livestock trampling, heavy machinery with the use of more powerful machines.
- Soil compaction is caused by the excessive or inappropriate use of chemical fertilisers and certain soil improvers.
- The repeated use of heavy machinery is a factor in soil asphyxiation and soil degradation or even regression, especially on fragile silty soils.
- The rate of water infiltration is affected by compaction with the possibility of loss of vegetation cover and accelerated soil erosion.

7) Soil pollution and contamination

- Agricultural soils can be polluted before or during their cultivation.
- Pollution is an adverse change in the natural environment that appears as a by-product of human action and corresponds to the accumulation of toxic compounds.
- Toxic compounds (chemicals, salts, radioactive materials or pathogens) have a negative effect on plant growth and animal health.
- Soil pollution generally means the contamination of one or more components of ecosystems.
- Soil pollution is due to the accumulation (on and in the soil) of non-biodegradable substances: MTE (metallic trace elements), PCBs (polychlorobiphenyls), dioxins,

PAHs (poly aromatic hydrocarbons), solvents used in industry, waste oils and pesticides.

- Soil pollution is also caused by the abandonment of pesticide packaging in the fields.
- The evolution of pollutants in soils will depend on their physico-chemical properties: biodegradable or not, highly soluble pollutants easily carried to the deeper layers of the soil.
- Pollutants adsorb, in a more or less sustainable way, on soil particles, particularly colloids (e.g. CHC).
- Some pollutants, including pesticides, are insolubilised and permanently settle in the solid phase of the soil.

PERSONAL NOTES AND REFERENCES OF THE MATERIALS USED

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LEAFLET 4

Preserve and restore soil fertility

TRAINING OBJECTIVES

At the end of this training sequence, the participant must be able to:

- understand the basic principles for preventing land degradation;
- know the techniques for controlling water and wind erosion;
- explain the role and importance of liming and various amendments in preserving soil quality;
- understand how to avoid salinisation, compaction or pollution of soil;
- know the techniques that allow the restoration of soil fertility: mulching, associated crops, the supply of organic matter (compost, manure, slurry) or fallow land;
- understand the interest of some soil remediation techniques by bioremediation.

KEY MESSAGES

1) Respect certain principles to prevent soil degradation

- Today, 33% of the land is degraded by erosion, salinisation, compaction, acidification and chemical pollution of the soil.
- To effectively prevent soil fertility degradation, it is necessary to analyse, at the level closest to the ground, the risks induced by the physico-chemical nature of the soil, farming practices, topography, climate and the type of crops planted.
- Respect for the soil begins with the reduction of tillage and the preference given to conservation agriculture: ‘ecological tillage’ and alternative techniques such as soil ‘scraping’, direct seeding and strip-till.
- Plant cover to protect the soil from heat, erosion, evaporation and leaching of nutrients by rain is necessary.
- Adopt the principle of ISFM by always combining fertiliser inputs with organic matter inputs to avoid soil acidification and better use fertilisers.
- Respect the integrity of the soil by avoiding the addition of toxic compounds: pesticides, heavy metals (present in some fertilisers), hydrocarbons, household waste.
- Amend the soil by adding corrective elements
- Use irrigation sparingly to avoid uncontrolled water inflows.

2) Adopt techniques to control water erosion

- The principle is land use planning (various techniques) on a slope to reduce and/or slow down water runoff.
- Stepped terrace techniques: these are constructions that break the slope but are more complicated and expensive to build.
- Stony barrier techniques: these are rows of stones arranged along contour lines to slow runoff, create a layered pattern and promote particle sedimentation.
- Logging techniques (simple or partitioned): allows to increase water infiltration by reducing the speed of runoff due to the roughness provided by these elements.
- The techniques for creating grassed strips: about 20 metres wide, they are installed on the slope, and promote infiltration and retain particles.
- Grassland restoration techniques: consist of periodic renovation and maintenance of grasslands, which is one of the most effective ways to reduce soil erosion.
- Management techniques: ensure the orientation, size and shape of the plots. The plots must be worked perpendicular to the slope to reduce runoff velocity, the risk of gullying and mudslides.
- The 'ridging tied' system: earth bunds built at regular intervals in the furrows make it possible to control the speed of the water. A simple and effective measure that can be combined with terrace construction and strip cropping to increase efficiency.

3) Adopt techniques to control wind erosion

- The strip cropping technique is a practice of dividing the farm into narrow fields with different crops, with or without fallow, and alternating strips of crops with strips of fallow or denser vegetation; it reduces wind erosion by decreasing the wind speed on the ground
- The addition of organic matter to the horizons, supplemental irrigation to increase the cohesion of the material help to limit wind erosion.
- Cultivation techniques that leave large clods or ridges on the ground surface perpendicular to the prevailing wind direction increase soil roughness and reduce wind speed on the ground surface.
- The installation of hedges, windbreaks, wind-permeable fabrics (5-10mm mesh) slow down wind speed, reducing evaporation and wind erosion.
- The mechanical and biological fixation of the dunes, to 1) extinguish the source of the sand and 2) to fix the dunes on site – in lines perpendicular to the wind and twenty times higher than these lines – is an effective system to stop wind erosion.

4) The role and importance of liming and the various amendments

- Calcium plays a decisive role in the physical, chemical and biological fertilisation of the soil and is a nutrient for plants.
- The role of calcium is not only to bind organic matter with clays: it regulates the mobility of metals, including iron involved in organo-mineral bonds.
- The calcium content in soils is constantly changing: it is the exchangeable calcium that is important.
- A distinction must be made between calcareous soils rich in active calcium, non-calcareous soils that are well endowed with exchangeable calcium and non-

calcareous soils that are poor in exchangeable calcium.

- Liming, in addition to contributing to the development of the plant, stabilises the clay-humus complex (CHC), stimulates activity by compensating for acidification and reduces toxicity by immobilising excess minerals.
- Maintenance liming keeps a satisfactory calcium condition. It consists of regularly making a basic amendment every 3 to 4 years to maintain the pH and restore to the soil the quantities of calcium and magnesium exported.
- Straightening liming consists of a greater supply of basic amendments to be able to straighten the pH of the soil, but it must be progressive and spread over several years.
- Calcium intake is based on lime and limestone, which can be either 'raw' or 'cooked' (heated to be active) products.

5) Avoid salinisation, compaction or soil pollution

- Better water management, leaching and drainage are effective ways to manage the risk of soil salinisation or reduce it.
- The measures to prevent soil compaction are based on 3 pillars: the planning of cultural interventions, the limitation of the loads supported by the soil and the control of the physical properties of the soil.
- The prevention of soil pollution, especially in agricultural areas, requires: the adoption of environmentally friendly agricultural and phytosanitary practices, the interception of pollutant flows at the farm level and the control of polluting products on the farm.
- The flow of pollutants such as the method of dispersal of pesticides and their residues is limited by strict compliance with Good Plant Protection Practices (GPPP).
- To better prevent soil pollution, hazardous waste should not be burned, especially not on the property of the farm.

6) Techniques that restore soil fertility

- Mulching consists of covering all or part of a degraded plot of land with organic matter for vegetation and soil reconstitution by maintaining moisture and developing biological activity.
- The practice of associated crops (mixed cropping, intercropping and relay crops) is defined as the simultaneous cultivation of at least two crops on the same plot during a significant phase of their growth, but not necessarily sown or harvested at the same time.
- Properly conducted, the practice of associated crops leads to an improvement in fertility because many plants with complementary needs are associated.
- The contribution of organic matter to the plot: organic matter is considered not only as a fertiliser, but also as a soil amendment.
- Organic matter is supplied to the plot either by the use of composts, cover crops, or by growing green manure, manure, slurry and liquid manure.
- 'Natural fallow' is the temporary interruption (for several months or years) of cultivation in a plot to allow the soil to replenish itself (organic matter).
- The so-called 'improved' fallow is a rotating system: carefully selected tree or shrub species are used in rotation with crops to improve soil fertility or produce economic goods.

7) Soil remediation techniques

- Bioremediation: a technique that involves inoculating the soil with micro-organisms, fungi, plants or enzymes.
- Bioremediation aims to increase and accelerate biodegradation or biotransformation to clean up a natural site.
- Phytoremediation: a technique that uses pollution-tolerant, fast-growing, high-biomass production plants competitive with the other plants on site for soil remediation by extracting the pollutant.
- Phytoremediation uses four main mechanisms depending on the nature of the pollutant and its physico-chemical characteristics.
- The four main mechanisms of phytoremediation are: phyto-extraction, phyto-degradation and phyto-sequestration, rhizo-degradation or bio-stimulation, and phyto-stabilisation.
- The physical treatment technique uses fluids (water, gas), present in the soil or injected, to transport the pollution to extraction points or to immobilise it.
- The chemical treatment technique uses chemical reagents to control pollutants.
- Thermal treatment technique: uses heat to neutralise the pollutant.

PERSONAL NOTES AND REFERENCES OF THE MATERIALS USED

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Summary of the manual

Sustainable soil management

1. DEFINITION OF THE SOIL, ITS IMPORTANCE AND COMPOSITION

The word 'soil' refers to all unconsolidated mineral and organic substances present on the Earth's surface and used as a natural environment for plant growth. In its traditional sense, soil is the natural environment for plant growth. It thus determines primary productivity and, consequently, life on Earth. The soil is differentiated from the Earth's crust by the significant presence of life. It is sometimes said that 'the soil is the living epidermis of our planet'.

Soil is also defined as a natural body consisting of superposed layers (or horizons, referred to as O, A, B, B, E, C...) that are composed of altered materials, minerals, organic matter, air and water.

The ability of a parcel of land to support agricultural activities provides a primary measure of its economic value. It is generally measured on the basis of the soil's ability to perform certain key functions that support production. It is not by chance that the richest societies developed in areas where the inherent fertility of the soil was high.

According to the African Soil Health Consortium (CAB, 2015), soil is the main input and production factor in agriculture. Soil is therefore the farmer's main 'asset', and its good management will economically enhance the value of the land in the long term. Soil is a source of food, biomass and raw materials, and provides storage, filtration and processing functions for many substances, including water, nutrients and carbon.

Definition and interest of sustainable soil management

Integrated soil fertility management aims at the optimal and sustainable use of soil nutrient reserves, mineral fertilisers and organic amendments.

According to FAO's definition, in the 'Voluntary Guidelines for Sustainable Land Management' (FAO, 2017), sustainable land management is characterised by the following 11 elements.

1. Low water and wind erosion of soils.
2. No degradation of the soil structure (e.g. no compaction), as the soil provides a stable surface that allows air, water and heat to circulate, as well as roots to grow.
3. Presence of sufficient vegetation cover (standing plants, plant residues etc.) to protect the soil.
4. A stable or increasing reserve of soil organic matter that is ideally close to the optimal level for the local environment.
5. Availability and circulation of nutrients to a degree appropriate to maintain or improve soil fertility and productivity, and to reduce fertility and productivity losses to the environment.
6. Low soil salinisation, sodisation and alkalisation.
7. Efficient infiltration and storage of water (from rainfall and complementary sources such as irrigation), *i.e.* to meet plant needs and ensure the drainage of any excess.
8. Concentration of contaminants below toxicity levels, *i.e.* likely to pose a danger to plants, animals, humans and the environment.
9. Soil biodiversity ensuring the full range of biological functions.
10. Land management systems based on optimised and safe use of inputs (in the production of food, fodder, fuel, timber and fibre).
11. Reduced soil sealing as much as possible, through responsible land use planning.

Sustainable soil management is a response to the global challenges of global food security for an environmentally sustainable agriculture focused on soil conservation and the environment.

Sustainable soil management is a **requirement of certain standards.** Thus, the **GLOBALG.A.P** standard has specific requirements regarding soils, maintaining their structure and preventing erosion, for example. Similarly, the Fair Trade specifications state that they are dedicated to ecological agricultural methods in order to protect and maintain biodiversity. Fair Trade aims at the limited and safe use of chemicals, waste management, erosion control, soil fertility maintenance and responsible water management. If managing soil fertility and developing sustainable production systems is a key concern in conventional agriculture, it is even more so in organic agriculture. In organic agriculture, one of the objectives of Regulation (EC) No. 834/2007 is to establish 'a sustainable management system for agriculture that respects natural systems and cycles, and maintains and improves soil health'. The Regulation therefore requires that soil management should not only maintain (or even improve) soil fertility (e.g. according to Article 12 in which fertility and biological activity of the soil are preserved and increased by multiannual crop rotation) but also prevent soil erosion and compaction.

The lack of soil fertility leads to lower yields and also favours the **development of many plant diseases.** If soil fertility is poor, crops **lack resilience and become more susceptible to drought,** disease and pests. The presence of the latter leads to a further decrease in productivity and further threatens the livelihoods of rural communities. To maintain soil fertility in the long term, it is necessary to first understand what a soil is made of and how it works.

Main mineral and organic components of the soil and their roles

Since soil formation is an extremely slow process, it can be concluded that it is essentially a non-renewable resource. According to the *Atlas of African Soils*, some soils in Africa can be very old and often reflect dramatic changes in climate and vegetation. Red soils dominate, indicating a high level of iron oxides. Almost half of Africa's land area is characterised by sandy (22%), shallow (17%) and poorly developed (11%) stony soils.

A soil sample consists (by mass) of minerals (up to 95%), water (15-35%), air (15-35%) and organic matter (0-5%) and three phases:

- a solid phase, composed of mineral components (sand, clay) and organic components (organic matter, MO);
- a liquid phase (also called the soil solution), composed of water in which soluble substances are dissolved;
- a gaseous phase, or soil atmosphere (or 'vapour phase'), composed of the same gases as air, with the addition of gases from the decomposition of organic matter.

The mineral constituents of the soil are: coarse elements (gravel, pebbles, sand and silt: diameter > 2 µm), coarse sands, fine silts and fine sands, clays or clay minerals (diameters < 2 µm). By **associating with organic matter,** fine clay particles participate in the formation of mixed colloids, **the clay-humus complex (CHC).** Mixed colloids are responsible for adsorption reactions that allow the binding of cations, anions or even charged molecules, such as pesticide residues and other soil contaminants.

Organic constituents are found in soil organic matter from the death of living things, their wastes and secretions. Vegetable substances account for almost all (99%) of the humus production. All soil organic matter includes fresh or slightly evolved organic matter and humic substances composed of organic macromolecules or 'colloids'. The advanced products are humic and fulvic acids. Thus **the soil represents the most important carbon sink** in the world (1,500 gigatonnes).

Soil formation, soil types and important soil properties

Soil takes a very long time to form and, under certain conditions, the mineral bedrock is altered by air and water. This allows the installation of the first pioneering plants. Then, the organic matter from dead plants and animals forms a litter on the surface. Decomposed by the soil fauna, it is transformed into humus. Then, when mixed with mineral elements, the soil becomes cultivable: this 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.

The formation of a soil involves several processes:

- disaggregation and alteration of bedrock (alteration);
- soil enrichment with organic matter (accumulation and incorporation);
- the migration of substances and particles into the soil profile (leaching of soluble elements and movement of particles).

According to soil scientists, six elements are fundamentally involved in soil formation:

- the composition of the bedrock (the parent material that will change);
- climatic conditions (climate is the engine of change);
- living organisms: vegetation and other (micro-)organisms;
- time (duration of events);
- the topography;
- human interventions (e.g. cultural practices, but also fires and deforestation).

Soil types

There are many variations and types of soil that only soil scientists are able to recognise and describe properly. Among the most representative soil types in ACP sub-Saharan African countries, we find mainly:

- desert soils;
- brown and brown soils;
- ferruginous, fersiallitic and vertisol soils;
- ferrallitic soils and brunizems.

Physical, physico-chemical and biological properties of soils

The **soil texture** gives **the proportion of mineral particles of different sizes.** The main particle size classes are clay (< 0.002 mm), silt (0.002 to 0.063 mm) and sand (0.063 to 2.0 mm). There are therefore 4 fundamental classes: sandy, silty, clayey or balanced texture. The texture can be estimated by touch between the fingers and measured by sieving and sedimentation. Textural classes may vary by country.

Soil structure refers **to the arrangement of soil particles** (also called aggregates) **and the space between them** (pores). Structure is therefore important for the movement of water and air, and for root development (soil porosity is an essential element to consider). There are 3 main types of structures: fragmentary, particulate or compact.

The type of soil structure **depends on biological activity**, physico-chemical and mineralogical characteristics, organic matter and soil management (agricultural practices, including the more or less intensive use of chemical fertilisers and pesticides). The biological properties of soils depend on the presence and diversity of species. There are more than 4,000 bacterial genotypes and more than 2,000 species of saprophagous fungi in the soil for the decomposition and production of OM. The soil contains up to 1,000 species of invertebrates: molluscs, insects, diplopods or myriapods, earthworms (burrowing), mites, springtails, nematodes and protozoa.

The clay-humus complex (CHC) represents **a structure formed of clay and humus.** Cation exchanges take place between the CHC and the soil solution: it is the CEC (cation exchange capacity). Soil acidity (pH) and soil buffering capacity are defined by the concentration of H^+ ion in soil water and buffering capacity is involved in stabilising soil pH.

The main functions of the soil

The soil is not just a 'substrate', and to reduce it to this simple and unique function would be a mistake.

First and foremost, **soil is involved in nutrient cycling, water and carbon storage, climate and pest control,** and the **conservation of global biodiversity.**

Soil participates in the cycles of nitrogen (N), phosphorus (P) and potassium (K), elements necessary for plant development. While representing one of the carbon sinks, soil participates in the carbon cycle by storing and releasing carbon into the atmosphere. Soils by releasing atmospheric carbon (CO_2) also contribute to global **climate regulation.**

Soil is a storage medium for **purifying** infiltrating **water**.

The soil is a **reserve of biodiversity.** It is a formidable factory to be transformed and created from living things because thousands of animal and plant species live in the soil. It is a place of life, rich in species and living beings: the many micro-organisms, invertebrates and bacteria form 80% of the biomass. In the soil, each species plays a role as a transformer of organic and mineral matter to make it usable by plants. The soil plays a role in regulating biological populations.

The soil is a source of raw materials for construction, to make kitchen utensils, for the extraction of energy or minerals.

2. INFLUENCE OF FARMING PRACTICES ON SOIL QUALITY

While farmers should manage soils as 'good fathers/mothers', it must be noted that under economic pressure they often adopt a set of practices that affect the fertility of their soils. Fertility degradation is a progressive phenomenon, its effects on production are not immediately felt but are increasing, leading the farmer into a deadlock. **Returning to a favourable situation then becomes more often than not complicated and requires not only a questioning of practices that have become customary, but also heavy investments** in time, manpower and other resources. More than ever, as far as soils are concerned, 'prevention is better than cure' because it is often too late to act and restore sufficient fertility. Some farming practices have a negative effect on soil quality. Others, on the contrary, are in favour of maintaining fertility.

Impact of some farming practices and their effects

- Ploughing makes seeding easier and allows crop residues, fertilisers and manure to be buried deeply and weeds to be destroyed. However, tillage is responsible for erosion and greatly promotes water runoff and sediment transport down the slope, leads to soil compaction and reduces soil porosity.
- Zero tillage such as strip till (limited tillage, on seeding strips only) or ridge till (on ridges), mulch till (surface tillage only without burial of crop residues) or direct seeding under cover combined with efficient crop rotation have a positive impact on soil quality.
- Non-tillage (direct seeding) takes about 5 years to reduce soil erosion by 90%. In no-till or direct seeding, acidification can increase in the surface horizon.
- Monocropping increases water and wind erosion, the risk of soil flooding and soil depletion through repeated sampling of the same elements.
- The crop association contributes to rapid soil depletion despite the improved nitrogen availability it provides in the association with legumes.
- Crop rotation achieves better root use and soil cover throughout the year if the order of crop succession is well chosen and supported by the incorporation of residual organic matter into the soil.

Impacts of the use of chemical inputs

Organic pollutants released into the atmosphere and falling back to the soil are a major problem because soils keep chemicals in 'memory': especially dioxins and PCBs (polychlorinated biphenyls), which are persistent pollutants in soils, or PAHs (poly-aromatic hydrocarbons), or heavy metals such as lead (Pb), cadmium (Cd), copper (Cu) and zinc (Zn). Industrial pollution is very high around urban centres, where industries and the high use of leaded fuel have contaminated the lead soil. But intensive agricultural practices can also have a lasting 'impact' on the soil.

There is a difference between soils grown in organic agriculture and those where mineral fertilisers, insecticides, fungicides and herbicides have been used for years: **biodiversity is decreasing, biological activity is decreasing, the structure is weakening.**

The following effects illustrate well the impacts of the use of certain chemical inputs.

- Some pesticides, dioxins and PCBs are persistent pollutants in soils.
- In the event of contamination by PAHs or heavy metals (kead (Pb), cadmium (Cd), copper (Cu), zinc (Zn)), which are industrial pollutants, the soil becomes unfit for cultivation, particularly in the lowlands or around mining sites.
- Mineral fertilisers and soil improvers also affect the properties of the soil: salinisation and acidification (acid pH). Some phosphate fertilisers contain cadmium (Cd).
- Some organic fertilisers (manure, pig manure) contain high concentrations of copper (Cu), zinc (Zn), cadmium (Cd) and lead, which are soil pollutants.

Production methods and impacts on soil fertility

Various production methods seek to conserve, improve or restore soil fertility. These modes of production are interesting to study because they make it possible to compare what is called 'conventional agriculture', which too often serves as a reference technical model, with other approaches, other ways of thinking about agriculture, the role of the soil, the interest of traditional techniques etc. All farmers have their own way of running their farms. It is very difficult today to validly define all modes of production and to classify them according to their 'sustainability', according to the various ways of exploiting and managing the land. Nevertheless, it is useful to try to differentiate them and explain their differences to the practitioner who is confronted with these concepts.

The various known production methods can be presented as follows.

- So-called 'conventional' or rather 'industrial' agriculture: it is highly mechanised, consumes a lot of fossil energy and inputs and, in the long term, damages soil quality: decrease in organic matter content, loss of structure, decline in soil biological activity, accumulation of toxic products in the soil.
- The so-called 'reasoned' agriculture: the contributions are reasoned and limited. Observations show that the long-term effect is to slow down the degradation of normal soil fertility.
- Integrated production: tillage is limited and soil fertilisation is practiced 'at the lowest possible level'; this is a step closer to the ideal of sustainable agriculture.
- Organic agriculture: it rejects the use of synthetic chemicals and combines best environmental practices, a high degree of biodiversity, the preservation of natural resources and protecting the soil in particular.
- Conservation agriculture, sometimes referred to as 'ecologically intensive agriculture': it restores the soil to its role as a pillar in plant production and is considered, not as an inert support, but as a living environment. It is perceived by users as a valuable tool for the sustainable management of the terroir. Conservation agriculture improves biodiversity and soil biological processes. It guarantees good agronomy, with targeted interventions over time to improve the general quality of the soil. It allows the integration of plants, livestock, trees and pasture.
- Permaculture: it is a mode of ecological land use planning whose three pillars are: caring for people and the land, producing and sharing resources equitably.
- Agroforestry: it refers to new or historical practices that combine trees, crops and/or animals on the same agricultural plot, on the edge or in the field. Agroforestry is based on the principle of complementarity (tree – soil – crops). It reduces the loss of soil nutrients and provides protection against erosion; it allows the control of cultivated areas by protecting soils and water; it combacts the greenhouse effect; the tree lifts water and minerals from the deep layers of the soil to make them available for surface crops. Agroforestry is a resource management system that is ecological, dynamic and natural, and that, by integrating trees into the landscape, allows for sustainable and diversified production, providing farmers with increased social, economic and environmental benefits.
- Zaï (basins or micro-basins to trap sand, silt from organic matter): it allows water to be concentrated locally, to control runoff and erosion, to restore the macroporisity and the production potential of degraded soil to be restored. Zaï revitalises the surface layer, corrects deficiencies, removes aluminic and manganic toxicities from the soil and improves its biological activity. Zaï homogenises the soils and secures production through its effectiveness in water management; it is a traditional cultivation technique originating from West Africa (Dogons of Mali, Niger, Burkina Faso), now mainly practiced by the population of northern Burkina Faso (Yatenga). It works well even when the rain is late, and even when the rain is missing. When the rain is good, the harvests are very good.

- Half-moon cropping technique: this is a method of rehabilitating degraded land to collect runoff water necessary for crop growth in arid and semi-arid areas. Half-moon cultivation uses the same principle as zaï, but these half-moons are more suitable for steeply sloping terrain. It increases infiltration and soil, stock, and it improves soil fertility and productivity. It allows to recover encrusted soil.

3. SOIL FERTILITY

Soil fertility is its ability to support crop production and, in this sense, fertility and productivity are synonymous. Fertile soil is a substrate that can support optimal plant growth, from seed germination to plant maturity. This support consists mainly of providing:

- adequate soil volume for root development of the plant;
- water and air for root development and growth;
- the chemical elements to meet the nutritional needs of the plant;
- the anchoring for the resulting plant structure.

However, a vision of fertility based on the physical components of the environment is too simplistic because the soil is not only an assemblage of organic and mineral elements, but it is preferable to consider it as a 'living being' that is born and then evolves under the influence of various factors including (micro)fauna, (micro)flora, and especially agricultural practices and its use by humans (Samake, 2007).

Soil fertility **depends on its origin** (alluvial soils, soils developed on different types of mother rock), its texture, structure, organic matter content and the producer's management of this fertility in the past (mineral and organic fertiliser inputs, crop precedents etc.).

To explain soil fertility, **two types of indicators** can be distinguished that evolve over time and are directly affected by agricultural practices.

- **Inherent soil quality parameters** refer to the characteristics of the soil in its natural state and allow it to function properly. These are soil texture and depth of bedrock, which can decrease as a result of erosion.
- **Dynamic soil quality parameters** that depend on how the soil is managed and include soil structure, soil organic matter content, and water and nutrient retention capacity.

The physical factors that determine soil fertility are many. These factors often interact with each other and influence soil fertility, *i.e.* its ability to produce.

Some of these also have an influence on the **sustainability of this fertility.** These are:

- **rainfall and temperature** (climate) influence soil fertility;
- the depth, texture, soil structure and physico-chemical properties of the soil determine its fertility.

Importance of organic matter for soil nutritional fertility and soil biology for soil fertility

It is necessary to know the importance of organic matter for the nutritional fertility of soils. To maintain soil fertility, the first step is to **preserve the organic matter** in the soil. For a long time the role of humus in plant nutrition has been minimised and the critical multifunctional roles that organic matter and soil biology play in providing plants with good amounts of minerals have been ignored.

The **presence of organic matter in the soil is essential to maintain its nutrient content for the plant.** It is humus, which gives the soil a dark colour, which allows it to retain a lot of water and nutrients.

If the soil is deeply deteriorated, the use of chemical fertilisers may become necessary to restore soil fertility very quickly.

Importance of soil biology for soil fertility

Most conventional agricultural systems have ignored **the key multifunctional roles of soil biology and its relationship to** agricultural land **productivity.** However, soil organisms are involved in both the physical and chemical aspects of soil quality.

Macro-organisms dig to great depths of large pores, or even galleries, facilitating drainage, aeration etc., and thus participate in soil maintenance, bedding burial, crust decomposition, soil particle movement and pore formation.

But it is the **micro-organisms that most affect soil fertility.** Their role is to:

- make nutrients available;
- improve soil structure by forming aggregates;
- capture and fixing nitrogen: numerous studies show that these micro-organisms produce a range of components that plants use to feed and protect themselves;
- increase **nutrient absorption:** the groups of micro-organisms that are beneficial for soil fertility are mycorrhizae and related fungi.

The highest concentration of soil micro-organisms is found in a narrow area near the roots of **plants.** Soil biology therefore plays many roles in optimising agricultural production, and any sustainable fertility management must avoid damaging soil life and balance.

How to assess soil fertility

The criteria for assessing soil fertility depend on:

- the depth: a great depth offers a large space for roots, and a great reserve of nutrients and soil water;
- its texture and structure show that medium grains and good structure are criteria for good fertility;
- the content of humus composition, nutrients and toxic products for soils, plants and humans;
- its mineralogical composition of the parental substrate: a homogeneous parental substrate results in a soil that is low in nutrients and provides an unbalanced diet;
- the reaction of the soil, which is reflected in the value of its pH: the pH close to neutrality (pH 6-7), promotes the assimilation of nutrients by plants.

Visual diagnosis allows the fertility of the soil by its colour, which is a good indication of its organic matter content and nature. 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. Farmers also estimate fertility based on a long-established knowledge of the indicator value of vegetation or certain observable signs on the soil surface. **Laboratory analyses are a useful complement to field observation to establish the diagnosis** and to better determine the qualities and defects of the soil.

Soil fertility is also determined by:

- tissue analysis as an indicator of soil fertility, which consists of determining the content of certain elements in certain plant organs;
- the analysis of plant tissues because the analysis of tissues gives indications on the nutritional quality of the soil;
- the diagnosis of the structure and biological activity of the soil by a soil profile which is the 'spade test' with macropores counting;
- counting and identification of earthworms;
- measuring the time of water infiltration (assessing soil porosity);
- a good observation of the shape and density of plant roots;
- microbial biomass analysis.

Soil fertilisation and fertilising elements

Fertilisation is the process of providing a growing medium, such as the soil (but also any other artificial substrate used in horticulture), with the mineral elements necessary for the plant's development. Fertilisers or 'fertilising materials' can be of **two types: chemical or organic.** They are presented in solid or liquid form.

Fertilisation remains **difficult for producers to control** despite the efforts made in extension. Their usual fertilisation practices are not **adapted to** sustainable production. They are often dependent on many factors such as the availability of organic resources, the availability of mineral fertilisers on the market and especially their purchasing power. Production growth can only come from an improvement in yields through the use of fertilising elements.

Fertilising materials, both chemical and organic, play an important role in agriculture because they:

- increase quantitative and qualitative yield, allowing farmers to make more profits in relation to the work provided and the products used;
- enable good yields with valuable crops through a wider choice of crop species that allows the farmer to adopt a more productive and advantageous cropping system. Under these conditions there is the possibility of diversifying production;
- allow the introduction of additional nutrients into the plant growth cycle and into the composition of plant debris, and thus improve fertility;
- indirectly increase the amount of crop residues that can be incorporated into the soil by ploughing;
- also play a role in product quality. For example, potassium fertilisation improves the potato's cooking performance, but can also reduce the flouryness of the flesh.

Fertilisation must always be rational, it must meet the objectives of sustainability, and also integrate the economic and environmental context. The farmer will have to **define his/her needs precisely according to his production objectives and production method.** He/she should take into account the nature of the soil and the requirements of each crop, within the framework of rotation or crop associations, as well as the mineral or organic resources available locally, in sufficient and adequate quantity and quality.

Role of the aqueous phase of soils in soil fertility

The sustainable approach is rather to **collect as much water as possible** to meet needs, rather than to bring water by irrigation. Water can be collected, for example, by installing structures to reduce runoff, slow the rate of water flow over the soil, or by covering the soil surface with organic mulch to promote infiltration and reduce evaporation at the soil surface.

Water is both a food source in terms of hydrogen and oxygen, **and a vehicle** that allows the roots to absorb dissolved fertilising elements. Most plants get the water and mineral salts they need from the soil. The roots that form the root system and the absorbent hairs located on the youngest of them play an essential role in this. Roots absorb mineral elements as ions, either from the soil solution, whether they are free or trapped in particular organic complexes, or from colloidal networks in the soil on which the elements are adsorbed.

The mineral elements adsorbed on the colloids or dissolved in the soil solution pass through two processes to the root:

- mass flow: transport by water of transpiration of plants;
- osmosis: movement of ions occurring under the effect of a concentration gradient, and dependent on the absorbency of the soil and the mobility of ions.

The absorption of mineral elements by the roots is a selective phenomenon and the plant chooses the elements most useful for its metabolism. It includes:

- a passive ion exchange phase on the root exchange surfaces, *i.e.* the cations are exchanged against the H^+ of the cell walls, essential to determine the cation exchange capacity;
- an active penetration phase that is covered by the energy provided by the breath. Each ion is transported by a specific carrier.

Soil water available to the plant or 'useful water' is the amount of water that the soil can absorb and return to the plant. Nutrients are only recovered by plants if they have enough water in the soil to absorb them.

4. THE CAUSES OF LAND DEGRADATION

Land degradation is mainly man-made and is a global phenomenon. Throughout the world, there are many examples of regions where soils have been seriously altered as a result of poor exploitation. The **soil can degrade rapidly** while it takes about 20000 years to form and regenerate. It is therefore essential to preserve agricultural quality and soil fertility.

The degradation rate of arable land is estimated at 25% in Africa, 38% in Asia, 21% in America, 11% in Europe and 5% in Oceania. The area of cultivable land is constantly decreasing, at a high rate of about 5 to 10 million ha per year. Soil degradation and loss of fertility is therefore an economic and ecological concern throughout the world, but the **consequences are felt most strongly by the poor populations of developing countries.**

The main manifestations of this soil degradation are related to **two scenarios.**

- Those that currently concern all soils directly used by man: 1) biological depletion and reduction of organic matter levels, and 2) soil compaction.

- The more localised ones, which for the moment concern only relatively limited areas of all the planet's cultivable surfaces: hydromorphology, salinisation, alkalinization, acidification, depletion of fine particles and nutrients, erosion or pollution. Unfortunately, these areas tend to increase, sometimes rapidly.

Gradual competition between different land uses, supported by insufficient sustainable soil management, leads to continuous degradation of soil properties and fertility. Today, **soil is a limiting factor in the supply of food,** both in quantity and quality, and a soil **conservation policy is essential in** agriculture.

The causes of the decline in soil fertility

Soil fertility decline can be defined as a deterioration of the physical, chemical and biological properties of the soil. According to a 1991 study, physical soil degradation is the most important and is largely directly related to human action. The decline in soil fertility or the deterioration of the physical, chemical and biological properties of the soil is largely directly related to human action.

The degradation of soil fertility can have **many causes.**

- Erosion, lack of cover, loss of organic matter and compaction cause deterioration of physical properties or soil structure.
- Salinisation, acidification, nutrient depletion damage soil chemistry. Pollution by industrial waste or by the excessive application of pesticides or chemical fertilisers also causes the deterioration of soil chemical properties.
- Biological degradation can be explained by certain cultural practices, the contribution of chemicals toxic to soil organisms, the decrease in soil organic matter content, the low pH, the combustion of biomass and the depletion of vegetation cover.

Soil erosion

Erosion is the stripping or process in which soil particles are removed. The mode of transport, and deposition of soluble and solid soil elements determine the type of erosion.

- Under the effect of water, it is water erosion: **water erosion** is a complex phenomenon, which particularly threatens the potential of water and soil. It is defined as the detachment and transport of soil particles from its original location by different agents to a deposition site. The three stages through which erosion occurs are detachment, transport and sedimentation.
- Wind-borne erosion is wind **erosion: wind erosion** can occur anywhere as long as soil, climate and vegetation conditions provide favourable terrain, *i.e.*.:
  - the soil is loose, dry, and fairly finely crumbled;
  - the soil surface is relatively even and the vegetation cover is absent or sparse;
  - the field is wide enough;
  - the wind is strong enough to initiate particle movement.

The speed and extent of wind erosion depends on the erodibility of the soil, the roughness of the soil surface and the climate. Erosion can be natural or human in origin, which is the anthropogenic erosion caused by tillage.

Erosion is a natural phenomenon that can have several effects:

- beneficial: deposit of fertile alluvium;
- harmful: to be a major danger to soils, either by selectively depleting the surface horizon of its vital substance, or by scouring the surface horizons sometimes down to the rock.

It is therefore **not necessarily desirable to stop all erosion,** but to reduce it to an acceptable, tolerable level. Indeed, erosion is at the origin of the rejuvenation of mountain soils and the formation of the most fertile plains. Erosion only becomes a problem when soil loss significantly affects productivity. This is unfortunately the case in much of sub-Saharan Africa.

Deforestation and overgrazing lead to land degradation

Forests are home to 80% of the world's terrestrial biodiversity, and most of the world's forests are of great benefit to humans. Forests cover, protect and conserve the soil; they provide energy and have an essential function in the fight against climate change. Vegetation is a very important source of carbon: 40% of the Earth's carbon is stored there. At the beginning of the 19th century, tropical forests covered an area of about 16 million km^2 worldwide. Today, less than half remain.

Animals are one of the major components of the food production system in arid, semi-arid and sub-humid regions. The value of manure has long been widely recognised in agricultural production. They are essential for sustainable agricultural production in most low and intermediate input systems.

As the area of cultivated land increases, the best soils are chosen for cultivation, so that the productivity of the remaining pastures decreases. Around water troughs, the vegetation cover can be destroyed and the soil compacted by trampling increases the amount of water that runs off. Deforestation refers to the destruction of forest areas as a result of overexploitation of the forest or in order to free up land for other uses. Each year, it wipes out some 13 million hectares of the world's forests. Deforestation is progressing rapidly in sub-Saharan Africa. The 'ecosystem services' provided by forests are valuable and multiple.

The **causes of deforestation** in tropical areas are the following.

- The expansion of agriculture: it is subdivided into several types of activities, all of which can lead to the conversion of forests.
- Wood extraction: timber is too often exploited in a devastating way in tropical regions exploited for their precious wood, then for their timber, and finally for the production of pulp.
- Charcoal production or use as firewood: wood is often the only fuel available or accessible to people to provide the energy needed to cook food and process agricultural products.
- Infrastructure and mining expansion: the impacts of the mining sector on forest cover are direct. These impacts are irreversible without rehabilitation action.

The **consequences of this deforestation are numerous,** including land degradation, loss of biodiversity, climate change, natural disasters, depletion of water resources and increased disease.

In fact, deforestation and overgrazing lead to land degradation.

- Deforestation leads to land degradation, loss of biodiversity, climate change (massive release of CO_2), natural disasters, depletion of water resources and aggravation of certain diseases.
- After deforestation, the regeneration of natural vegetation takes a long time (about 20000 years).
- Overgrazing: pressure on grazing areas leads to a loss of edible vegetation and a dominance of shrub species, leading to desertification.

Soil salinisation

Soil salinity results from the presence of dissolved major mineral solutes in water or soil. Soil salinisation refers to **the gradual increase in the concentration of water-soluble salts in the soil solution,** under the influence of natural factors.

Salt soils cover large areas on all continents and in all climates. Soil salinisation is a way in which soil productivity can be reduced without loss of soil cover, a scenario similar to that of soil pollution by chemicals.

Salinisation is most often the result of irrigation of poorly drained soils in arid climates. The stagnation of water in the upper layers of the soil due to poor drainage results in an accumulation of salts in the most superficial horizons, because upward movements, linked to the strong evaporation due to the hot and arid climate, greatly exceed infiltration and thus leaching.

The consequences of salinisation are the following.

- The accumulation of soluble salts, in particular sodium salts, on the soil surface and in the root zone causes harmful effects on plants, leading to lower yields and even soil sterilisation.
- The most serious danger to the soil is the excessive quantity of water that causes it to become clogged and raises the level of groundwater. Osmotic pressure in the soil solution prevents water from entering the plant.
- Changes in pH can also occur as a result of salinisation phenomena.
- Salinisation also reduces the microbial activity of the soil that is the basis of nitrification processes.

Market garden and tree crops are generally more sensitive to salt concentration in the root zone than cereals. Soil salinity is assessed by ion analysis methods and its salinity tolerance threshold is specific to each plant species.

Soil compaction

Compacted soils are less productive, more sensitive to erosion and contribute less to the purifying and 'buffering' functions of soils. All over the world, the soils used by humans tend to settle, losing their porosity, often by 10 to 50 cm. This compaction is most often due to agricultural machinery, but overgrazing and overcrowding of an area by humans can contribute locally. Compaction has various impacts.

- Compacted soils caused by livestock trampling and/or heavy machinery with the use of more powerful machines are more sensitive to erosion, contribute less to the purifying and 'buffering' functions of soils. Soil compaction can also be caused by the excessive or inappropriate use of chemical fertilisers and certain soil improvers.

- The repeated use of heavy machinery is a factor in soil asphyxiation and soil degradation or even regression, especially on fragile silty soils.
- The rate of water infiltration is affected by compaction with the possibility of loss of vegetation cover and accelerated soil erosion.

Soil pollution and contamination

Soil is considered polluted when it contains an **abnormal concentration of** chemical compounds that are potentially harmful to plant or animal health. Agricultural soils can be polluted before or during their cultivation. This is why it is important to know the 'soil history' over several years, especially in the context of certain certifications (e.g. GLOBALG.A.P. which requires it).

Pollution is an adverse change in the natural environment that appears as a by-product of human action, through the direct and indirect effects of its activities. These changes can affect humans directly or through resources of agricultural products, water, and other biological products. **Soil pollution is the accumulation of toxic compounds:** chemicals, salts, radioactive materials or pathogens, all of which affect plant growth and animal health.

In an 'environmental' approach, the soil is interfaced with water and air. The notion of soil pollution therefore generally also requires the contamination of one or more components of ecosystems or organisms living in direct or indirect contact with the soil that have an impact on the ecosystem, above thresholds that vary according to the nature of the pollutant and the soil. The effects of soil pollution depend on soil structure and texture. Some soils have the ability to filter, absorb and recycle significant amounts of waste; in other soils, some toxic constituents are not retained and end up in rivers and groundwater. Sandy soils are conducive to leaching, while thick clay soils retain pollutants better. Thus, all human activities on the soil must take into account the properties of the soil, and the position of the groundwater table and watercourses in the environment.

In addition to toxic compounds such as chemicals, salts, radioactive materials or pathogens, other factors negatively affect plant growth and animal health, such as:

- soil pollution, caused by the accumulation (on and in the soil) of non-biodegradable substances: MTE, PCBs, dioxins, PAHs, solvents used in industry, waste oils and pesticides;
- soil pollution, also caused by the abandonment of pesticide packaging in the fields;
- the evolution of pollutants in soils, depending on their physico-chemical properties: biodegradable or not, highly soluble pollutants easily carried to the deeper layers of the soil.

Pollutants adsorb, in a more or less sustainable way, on soil particles, particularly colloids (CHC) and some pollutants, including pesticides, are insolubilised and permanently fix in the solid phase of the soil.

5. PRESERVE AND RESTORE SOIL FERTILITY

Today, 33% of the land is moderately or severely degraded due to erosion, salinisation, compaction, acidification and chemical pollution of the soil. The current rate of land degradation threatens the ability of future generations to meet their most basic needs. However, there is a growing awareness of the need for a general reform of reference agricultural practices.

The 'agri-environmental' measures within the framework of agricultural policy in Europe are aids to farmers to promote, among other things, soil protection actions. The Rio Convention on Biological Diversity (CBD) has established an international initiative for the conservation and sustainable use of soil biological diversity. Various States, such as the USA, Japan, Canada, Australia, Brazil and some developing countries, have created soil observation and protection policies.

Understand and respect some basic principles to prevent soil degradation

To effectively prevent soil fertility degradation, **it is necessary to analyse, at the level closest to the ground, the risks induced** by the nature of the soil and its organic matter content, farming practices, especially tillage and fertilisation, topography, particularly the slope, climate, especially rainfall patterns, and the type of crops planted, *i.e.* soil cover.

Adherence to a number of basic principles will already significantly reduce or slow the risk of fertility degradation.

- Reduce **tillage** to what is really necessary and prefer the approach adopted by conservation agriculture: 'ecological tillage' and alternative techniques.
- **Plant cover** to protect the soil from heat, erosion, evaporation and leaching of nutrients by rain.
- **Adopt integrated soil fertility management (ISFM)** by always combining fertiliser inputs with organic matter inputs.
- Amending the soil: providing it with elements such as organic matter and lime, which will make it possible to maintain a good structure on the one hand, and to naturally boost its biological activity on the other hand.
- Use irrigation sparingly: avoid uncontrolled water inflows, and ensure good drainage to avoid salt accumulation in the top layer of the soil.
- Respect soil integrity: avoid polluting the soil with toxic compounds: pesticides, heavy metals present in certain fertilisers or manure, hydrocarbons, household waste.

Opt for techniques to control water and wind erosion

Soil erosion is one of the most critical problems facing agriculture today. This concern has led to the experimentation and development of techniques to control **water and wind erosion.**

The fight against water erosion requires knowledge of the causes of this type of erosion, the evolution of the process and the relationships between erosion and soil conditions. Then, we can choose the **improvement and control measures** that are always based on the following principles:

- reducing the force of the impact of raindrops;
- improving the stability or resistance of the soil;
- reducing the amount of water causing runoff;
- reducing water speed and controlling runoff discharge;
- reducing soil compaction: Soil compaction and wheel marks that concentrate water increase runoff.

The presence of a crop that covers the soil well is an effective way to control water erosion because, first, it reduces the force of rain drop attack. Secondly, it reduces the speed of runoff water and finally increases the stability of the soil, its permeability resulting in the infiltration capacity of the water.

The fight against wind erosion is organised on two levels: increasing the cohesion of the material in the face of this aggression and reducing the wind speed at the soil surface. The principles of control are based on:

- an increase in the **cohesion of the material**: the addition of organic matter to the soil's surface horizons improves its structure;
- an increase in the **roughness of the soil surface:** these are cultivation techniques that leave large clods or ridges on the soil surface perpendicular to the prevailing wind direction.

In areas subject to high winds, but with **regular directions**, the installation of hedges and windbreaks are appropriate methods. They **slow down wind speed to** reduce evaporation and wind erosion. In the event that dangerous winds blow from **several sides,** wind-permeable fabrics are used instead, thanks to a mesh size of about 5 to 10 mm.

For very desert and sandy areas, **dune fixation** is also effective and efficient. Its purpose is, on the one hand, to extinguish the source of the sands and, on the other hand, to fix the dunes in place.

The role and importance of liming and the various amendments

The **role of calcium is not only to bind organic matter with clays:** it regulates the mobility of metals, including iron involved in organo-mineral bonds. A distinction must be made between calcareous soils rich in active calcium, non-calcareous soils that are well endowed with exchangeable calcium and non-calcareous soils that are poor in exchangeable calcium.

Calcium plays **a decisive role on two levels.**

- First, action on fertilisers:
  - physical, by **stabilising soil structures,** with reduced sensitivity to beat and improved gas and water exchange;
  - chemical, through the operation of the CEC, with desalination;
  - biological, with the activity of the microbial biomass of the soil.
- Secondly, calcium is also **a nutrient** for plants.

Calcium (liming) is provided from lime and limestone, which can be either 'raw' or 'cooked' (heated to be active). In organic farming, the products authorised by the regulations are calcium carbonates of natural origin. **Liming**, in addition to contributing to the development of the plant, **stabilises the clay-humus complex (CHC), stimulates activity** by compensating for acidification, reduces toxicity by immobilising excess minerals.

There are two types of liming:

- **maintenance liming**: it preserves a satisfactory calcium state to maintain the correct pH and restore the quantities of calcium and magnesium exported to the soil;
- **straightening liming:** it consists of **more important, but progressive, contributions of** basic amendments to be able to straighten the pH of the soil.

Salinisation, compaction or pollution of soil

Soil degradation and improvements **thus vary according to location, land use and the objectives of agricultural stakeholders.** There are several ways to prevent or correct salinisation: better water management, leaching, drainage and finally flooding of land are effective ways to manage the risk of soil salinisation or reduce it. The proposed solutions to soil compaction problems can be divided into **two categories:** preventive and curative measures.

In general, to avoid salinisation, compaction or soil pollution, the following practices should be instituted.

- **Measures to prevent** soil compaction, which are based on 3 pillars: planning cultural interventions, limiting the loads supported by the soil, and controlling the physical properties of the soil. To better prevent soil pollution, hazardous waste should not be burned, especially on the property of the farm.
- The adoption of environmentally friendly **farming and phytosanitary practices,** with the interception of polluting flows at the farm level and the control of polluting products on farms to prevent soil pollution, especially in agricultural environments.
- Strict **compliance with Good Plant Protection Practices (GPPP)** to limit the flow of pollutants such as the method of dispersal of pesticides and their residues.

Restoring soil fertility

Organic matter in the soil plays a very important role in view of its potential beneficial effects on soil and crops. Therefore, all techniques that aim to improve or preserve soil fertility have **one thing in common: the enrichment of the soil with organic matter.**

The techniques that allow the restoration of soil fertility are essentially the following.

- **Mulching of the soil:** it consists of covering all or part of a parcel of degraded land with organic matter for vegetalisation and reconstitution of the soil.
- The **practice of associated cultures:** these are mixed cropping, intercropping and relay cultures.
- The **addition of organic matter to the plot:** not only as a fertiliser, but also as a soil amendment is very effective.
- '**Natural fallow**': it consists of temporarily interrupting cultivation in a plot for several months or years to allow the soil to replenish organic matter.
- '**Improved fallow**' is a rotating system where carefully selected tree or shrub species are used in rotation with crops.

Soil remediation techniques

There are very few techniques for soil remediation, except for the extraction of the polluted mass. For organic compounds, soil micro-organisms can 'digest' molecules but only if they are 'bioavailable', *i.e.* not adsorbed/fixed to soil particles. In this case, we are talking about **bioremediation.** For heavy metals, some plants can extract them from the soil and concentrate them, this is called **phytoremediation.**

- Bioremediation is the technique that uses the inoculation of soil with micro-organisms, fungi, plants or enzymes to increase and/or accelerate biodegradation to naturally clean up a site.

- Phytoremediation is the technique that uses pollution-tolerant, fast-growing, high-biomass production plants that are competitive with the plants on site for soil remediation by extracting the pollutant. The technique uses four main mechanisms depending on the nature of the pollutant and its physico-chemical characteristics. These are: phyto-extraction, phyto-degradation and phyto-sequestration, rhizo-degradation or bio-stimulation and phyto-stabilization.

Some other treatments are theoretically possible:

- physical treatments that use fluids (water, gas), present in the soil or injected, to transport the pollution to extraction points or to immobilise it;
- chemical treatments that use chemical reagents to control pollutants;
- heat treatments that use heat to neutralize the pollutant.

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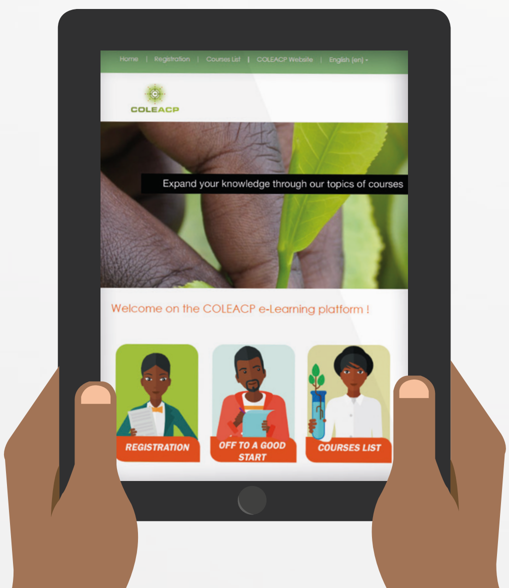

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