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Module

Soil physics

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Chapter 1: Physical Properties of Soil

1. Constituents of Soil

The soil environment is complex, comprising both mineral and organic components. Mineral constituents make up 93 to 95% of the total weight of the soil. The mineral fraction of the soil results from the disintegration and weathering of underlying rock.

Mineral constituents of the soil are classified based on their size through soil particle size analysis, known as granulometric analysis. This categorization includes gravel, sand, silt, and clay; their relative proportions define the soil texture (table 1).

Table 1: Classification of Mineral Particles Based on Size.

Category	Pebbles	Gravel	Coarse sand	Fine sand	Coarse silt	Fine silt	Clay
Extreme diameter	20 -5 cm	20cm-2mm	2 - 0.2mm	0.2 - 0.05 mm	0.05 - 0.02 mm	0.02 - 0.002 mm	<0.002mm

1µmètre = 0.001 mm ⟶ **1000 µmètre = 1 mm**

Note: The coarse fraction of the soil, consisting of sands and silts in terms of size, is referred to as the soil skeleton. This fraction is chemically quite inert because these grains carry little electrical charge, and their specific surface area (surface developed per unit mass) is low.

It is the smallest mineral constituents, the clays, that exhibit greater chemical reactivity due to the surfaces they develop and their charges.

1.1. Clays

1.1.1. Definition 1: In the agronomic sense, clay is the mineral fraction of soil with particles smaller than 2µm.

1.1.2. Definition 2: In the mineralogical sense, clays are phyllosilicates whose basic structural unit is a well-defined sheet. The sheets consist of layers of silicon tetrahedra (Te) or aluminum octahedra (OC). The sheet is constructed from either two layers Te-OC or three layers Te-OC-Te.

1.1.3. Tetrahedral layer: Comprised of Si+4 tetrahedra surrounded by four O^{-2} anions at the vertices (fig.1).

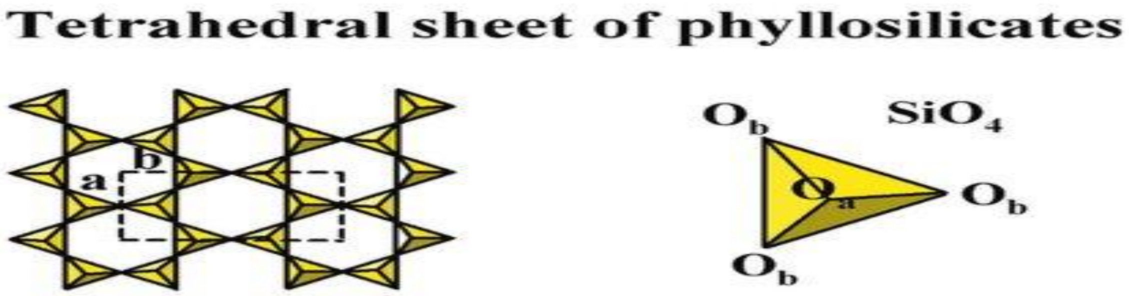


Fig.1 : Tetrahedral layer (Cecilia, et al, 2018).

1.1.4. Octahedral layer: Consists of Al^{+3}, typically surrounded by six hydroxyls (OH^{-}) or O^{-2} (fig.2).

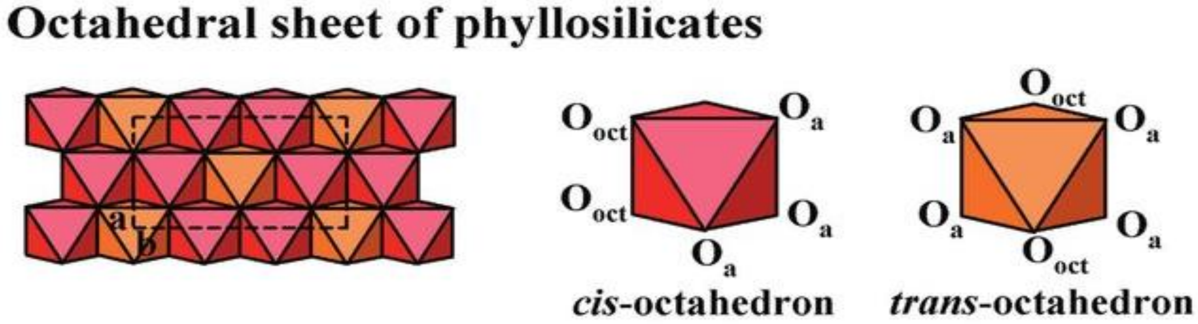


Fig.2 : Octahedral layer (Cecilia, et al, 2018).

1.1.5. Clay Structure: Three types of clay minerals are differentiated based on the number of layers constituting the sheets (fig.3).

1.1.5.1. Type 1/1: Te / OC, is the simplest, with a two-layer sheet, one tetrahedral (Te) made of silica and one octahedral (OC) made of alumina, with a fixed thickness of 0.7 nm (7 Ångströms). Kaolinite belongs to this group (fig.3).

1.1.5.2. Type 2/1: Te / OC / Te, consists of a three-layer sheet, with two layers of silica surrounding one layer of alumina, as seen in illites (constant thickness of 1 nm) and vermiculites (variable thickness from 1 to 1.5 nm). This category also includes swelling clays like smectites and montmorillonites, where sheet thickness can reach 2 nm through hydration.

1.1.5.3. Type 2/1/1: Te / OC / Te / OC, comprises a three-layer sheet, supplemented with an additional octahedral layer based on magnesium. These clays have low exchange capacity. Chlorites, which do not swell, belong to this category, with the thickness of the sheets remaining fixed.

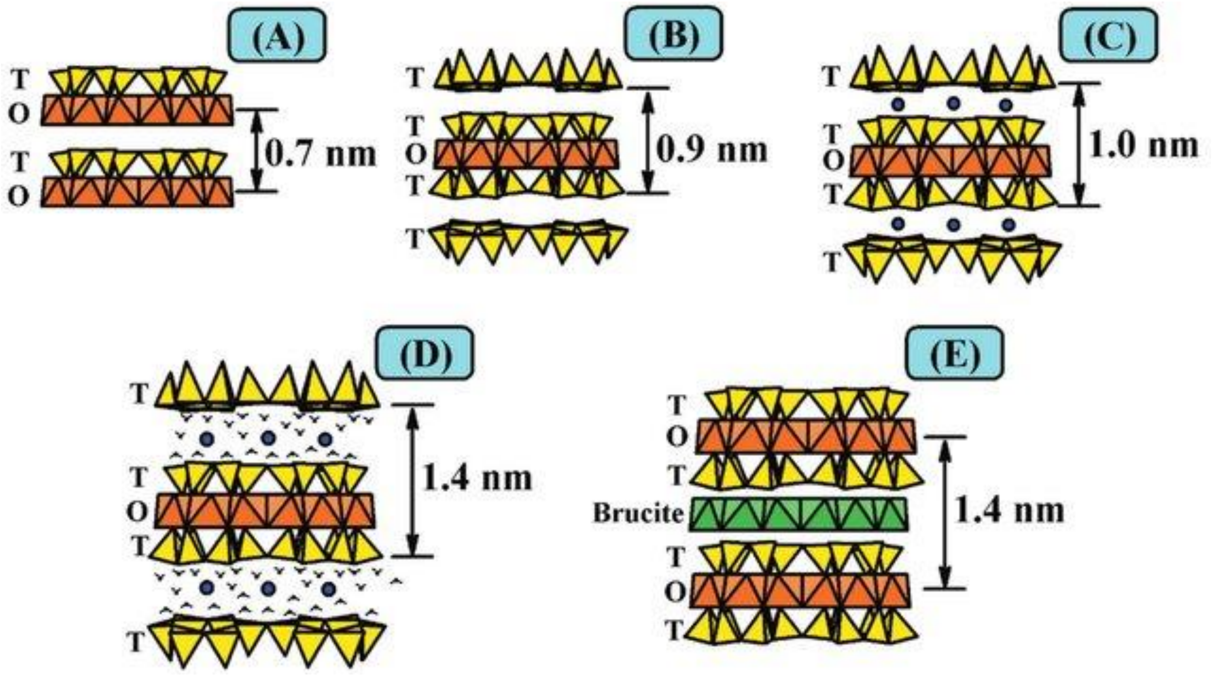


Fig.3 : Structures of phyllosilicates. (A) Kaolin and serpentine, (B) talc and pyrophyllite, (C) mica, (D) smectite and (E) chlorite (Cecilia, et al, 2018).

1.2. The organic constituents

It originates from the activity of all organisms present on or within the soil. A portion of this organic matter is produced by living organisms: animal excreta, root exudates, and plant litter, microbial polysaccharides. The remainder consists of debris from dead plants, animal carcasses, and lysed microbial cells.

The organic fraction represents an average of 5% by weight and 12% by total volume of the soil.

1.2.1. Soil organic matter categories

Soil organic matter can be broadly grouped into four categories:

1.2.1.1. Plants and living organisms: on the soil and within the soil, represent several tons per hectare.

1.2.1.2. Organic debris from plants and animals, still organized or fresh organic matter : that returns to the soil, has a composition similar to the living tissues from which they originate:

Hydrocarbon substances (composed of C, O, H): soluble sugars, starch, cellulose, lignin, fats, resins, etc.

Nitrogenous matter, mainly in the form of proteins, composed of C, O, H, N, and also P and S.

Minerals associated with the preceding substances: salts and ions of calcium, magnesium, potassium, sodium, etc.

1.2.1.3. Transient products: are the links in this transformation chain starting from fresh organic matter with very large molecules and ending, for most of these molecules, in simple mineral substances with small molecules:

- Carbon dioxide and water
- Mineral substances: nitrates, phosphates, carbonates, sulfates of potassium, calcium, magnesium, sodium, etc.

1.2.1.4. Humus: a new and complex substance, truly reconstructed from certain organic (transient) and certain mineral materials.

1.2.2. The stages of organic matter evolution

1.2.2.1. First stage: Primary mineralization

It is a disaggregation, a decomposition, a return to the mineral state of the components of fresh organic matter.

The complex molecules of fresh organic matter first undergo microbial decomposition, meaning a transformation that releases simple compounds, often soluble. A portion undergoes the process of mineralization, transforming into soluble or gaseous mineral compounds.

Among these released substances, we find:

- CO2
- Des matières minérales assimilables par les plantes : azote nitrique, phosphates et sulfates de calcium, de magnésium, de potassium, de sodium, oligo-éléments… Ces matières minérales sous forme d’ions peuvent connaître 5 destinations :
- Assimilated by plants
- Adsorbed on the clay-humic complex
- Lost to the atmosphere
- Lost through leaching
- Taken up by certain microbes for the synthesis of humic compounds; it is microbial humin.

$$\underset{\text{macromolecule}}{\text{FOM}} \xrightarrow[\text{Fauna + microorganisms}]{\text{Decomposition}} \text{simple biomolecule (monosaccaride, monophenol, amino acid, fatty acid)}$$

$$\underset{\text{A portion}}{\text{Simple biomolecule}} \xrightarrow[\textit{Microbial Enzyme}]{} \text{Mineral molecule } (CO_2, H_2O, HPO_4^{-2}, SO_4^{-2}, K^+, Ca^{2+}, Mg^{2+}, NH4^+, Na^+ \ldots.$$

1.2.2.2. 2nd step: Humification: Another portion escapes mineralization, serving as material for the construction of new, increasingly complex molecules, of colloidal nature and dark color, together forming humus.

1.2.2.3. The three pathways of humification:

The pathway of insolubilization: several aromatic nuclei can fuse through oxygen or nitrogen bridges (fig.4).

At first, dimeric or trimeric compound (2 or 3 phenolic nuclei) are formed, giving rise to **creneic and hematomelanic acids**, and then to **fulvic acids**. As polymerization continues, fulvic acids soon give rise to **humic acids** and finally to **insolubilization humin**.

This polymerization or polycondensation is characterized by several phenomena:

- Increase in the size of the aromatic nucleus
- Decrease in the proportion of aliphatic chains
- Increase in molar mass
- Progressive conversion of nitrogen from the amino form in aliphatic chains to the heterocyclic form in the nucleus
- Increasingly strong binding with mineral constituents: clay, sand, silt.

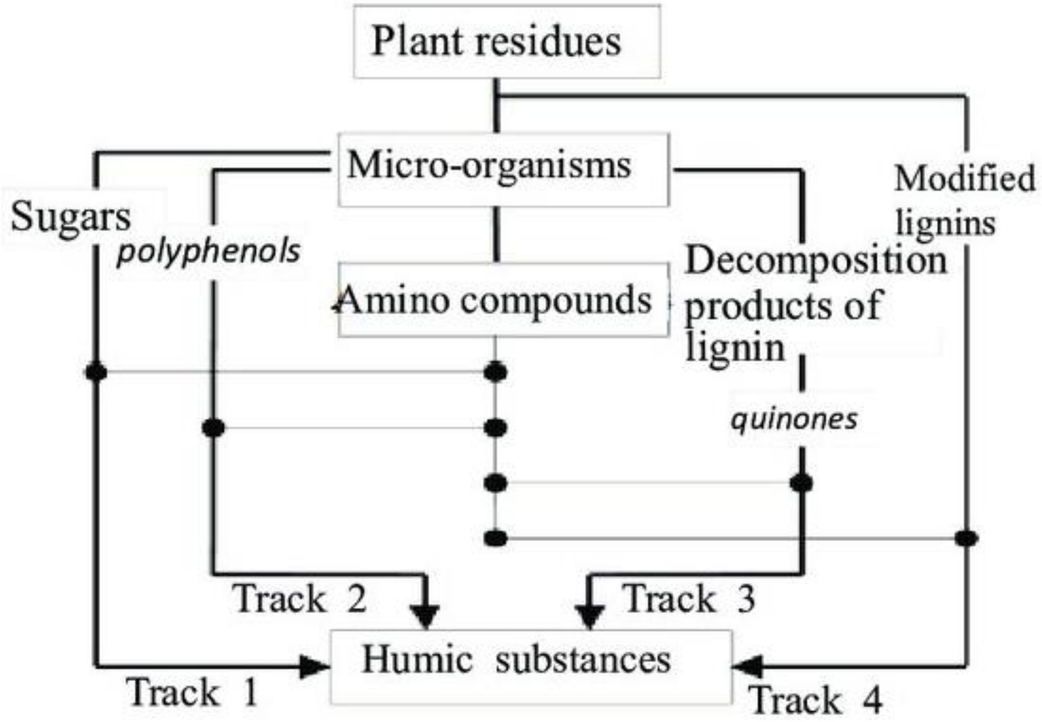


Fig. 4: The pathways of humification.

The inheritance pathway: whenever the decomposition of lignin is blocked for any reason, its slightly transformed molecules bind more or less to the mineral matter, especially in the digestive tract of soil fauna, to form insoluble humin, referred to as ***residual humin or inherited humin***. The blockage could result from:

- Excess acidity
- Anaerobiosis
- Excess active lime.

The pathway of microbial neosynthesis

Certain microorganisms have the ability to take up simple molecules resulting from primary mineralization to synthesize their own substance. Upon their death, the polysaccharides resulting from their biodegradation can bind to mineral matter to form another fraction of humus, called microbial neosynthesis humin.

1.2.2. 3. 3rd step: Humus mineralization or secondary mineralization: under the action of other microorganisms, the entirety of humus compounds is more or less rapidly attacked and eventually reverts to the state of simple molecules (fig.5). These molecules can be:

- Lost to the atmosphere
- Absorbed by plants
- Adsorbed by clay and humus
- Lost through leaching.

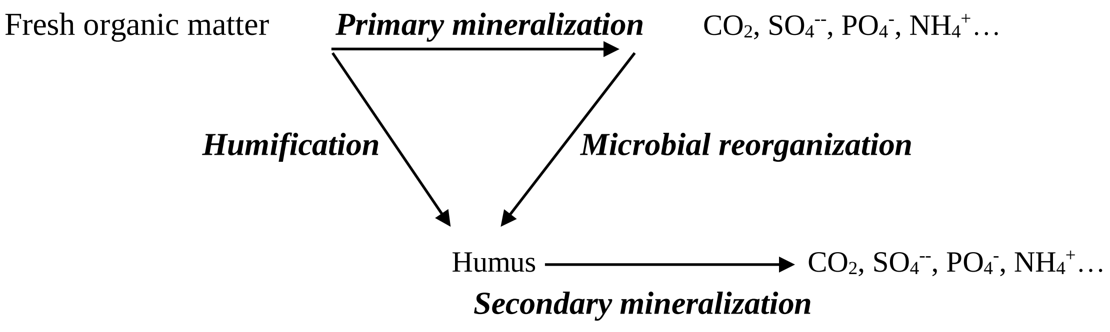


Fig.5: Decomposition of fresh matter.

2- Soil Texture

Soil texture refers to the composition of mineral particles (sand, silt, and clay) in a particular soil sample and the relative proportions of these particles. The texture of soil greatly influences its properties, such as water retention, drainage, and fertility.

2.1. Texture Classes: Soil texture is classified into four main categories

2.1.1. Sandy Texture: Well-aerated soil, easy to work, low in water retention, low in nutrients, and low cation exchange capacity.

2.1.2. Silty Texture: Excess silt and insufficient clay can lead to the formation of a massive structure, accompanied by poor physical properties.

2.1.3. Clayey Texture: Chemically rich soil but with poor physical properties, featuring an impermeable and poorly aerated environment that hinders root penetration and makes soil cultivation difficult.

2.1.4. Loamy Texture: Balanced soil that represents an optimum with most qualities of the previous three types but without their drawbacks. Example of favorable particle distribution for cultivation: 25% clay, 30-35% silt, 40-45% sand.

2.2. Methods of Texture Determination Texture can be assessed in the field or deduced from particle size analysis, which precisely determines the proportions of various particles distributed in size classes.

2.2.1. On-site Texture Determination (by touch) Some specialists, especially agronomists and soil scientists, can approximately determine, after moistening, whether the soil is more clayey, silty, or sandy. Indeed, clay sticks to the fingers, silty soil feels smooth, and sandy soil feels gritty to the touch (table 2).

Table 2: Test for estimating the dominant texture of soil.

test	**Result**	**Consequence on the texture**
Touching dry soil	Silty or talc-like	Abundance of fine silts
	Soapy	Abundance of coarse silts
	Rough	Coarse sands
Creating a sausage-shaped clump of moist soil	Possible	Clay >10 %
	Impossible	Clay < 10 %
Creating a ring with the soil clump	Cracking before 1/2 closure of the ring	Silt > Clay Clay < 30 %
	Cracking at 3/4 closure	Silt < Clay Clay < 30 %
	Ring achievable	Clay > 30 %
According to A. Fleury et B. Fournier, INA P.G.		

2.2.2. Laboratory Texture Determination

Back in the laboratory, for a more detailed texture determination, the sample's sand, clay, and silt content are assessed. Then, a diagram is used to determine the soil texture class, such as silty, sandy-clay, silty-clayey (fig.6).

For example, if the soil has 40% sand, a line is drawn parallel to the silt side and perpendicular to the sand side at 40%. Similarly, for 20% clay, a line is drawn parallel to the sand side and perpendicular to the clay side at 20%. The point where these two lines intersect corresponds to the texture of the soil. The third parallel line helps deduce the silt content (40% in this example).

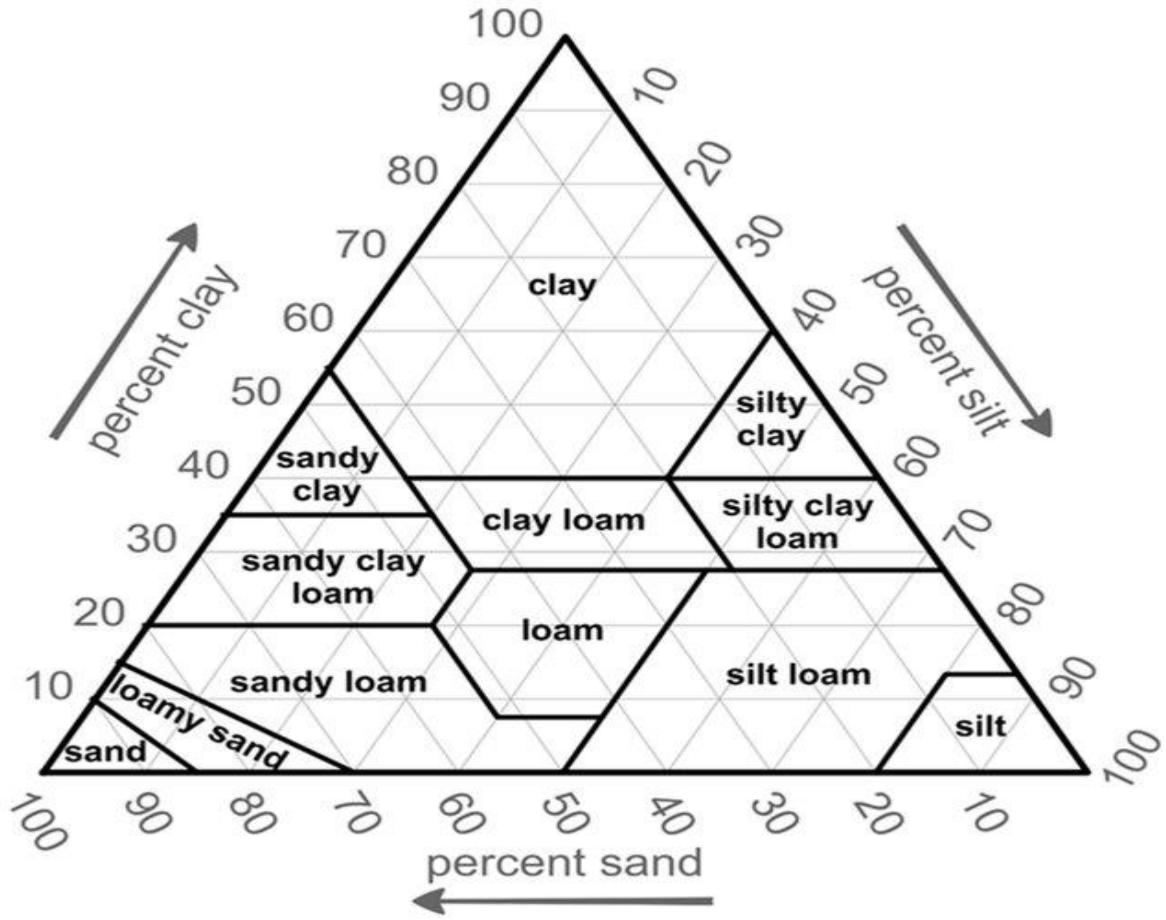


Fig. 6: Texture Triangle.

Example:

- 20% clay, 40% sand, 40% silt: Silty texture
- 5% clay, 90% sand, 5% silt: Sandy texture
- 40% clay, 50% sand, 10% silt: Sandy-clay texture
- 10% clay, 20% sand, 70% silt: Fine silty texture
- 30% clay, 60% sand, 10% silt: Silty sandy-clay texture.

3- Soil Structure

3.1. Definition of Soil Structure: It is the mode of assembly, at a given moment, of its solid constituents.

3.2. Definition of Aggregate: The basic structural element, defined by more or less regular geometric shapes, may contain all the elements of fine earth (sand, silt, clay), possibly even gravel or stones (fig. 7).

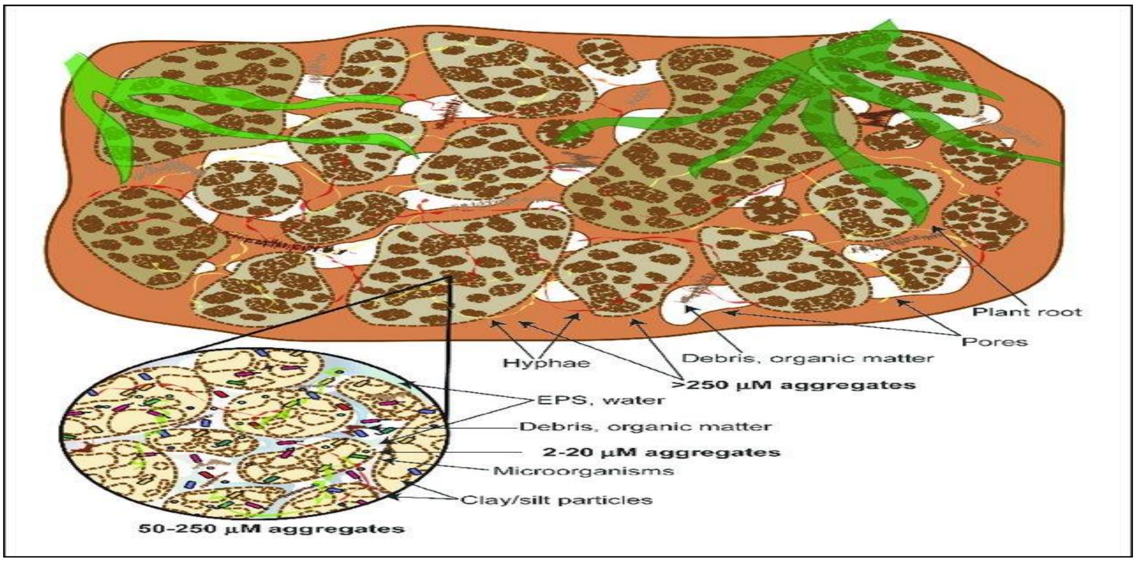


Fig. 7: Formation of an Aggregate.

3.3. Agents of Aggregate Formation (of structure) : Develops under the influence of external factors: climate, biological activity, human activity.

The elementary particles are held together by the presence of colloidal cements (clay and organic matter) and oxides and hydroxides.

- The most important cementing agents actively involved in soil structure formation, in order of importance, are: microbial gums (polysaccharides) > iron oxides > organic matter > clay.
- Sustained microbial activity supported by organic matter, closely related to aggregate formation. Microorganisms can intervene in various ways:
  - Through the mycelium of fungi, which connects soil particles
  - Through polysaccharides and other products of microbial metabolism that act as cementing agents.
  - Some microorganisms produce charged substances (+ or -) that form a bond between the mineral particles of the soil.

-Soil aggregates can be formed by freeze-thaw cycles.

3.4. Types and Classes of Soil Structure: There are mainly three types of structure:

3.4.1. Particulate Structure

A soil or material without structure is mainly composed of individual particles not associated with each other by cohesive forces. Example: sea sand, dune sand...

It is characterized by a very high infiltration capacity but a very low retention capacity, making the soil uncultivable. However, there is a specific flora adapted to these particular conditions, with, for example, deep roots and reduced transpiration.

3.4.2. Compact Structure (continuous)

The entire soil layer or the face of a profile (or horizon) then forms a single block. In contrast to particulate structure, it severely limits water infiltration into the soil, causing waterlogging. The soil becomes oxygen-depleted and is difficult for roots to penetrate. However, some plants tolerate these living conditions. There are three types of continuous structure:"

- **Continuous Cement-like Structure**: The majority of elements are very fine.
- **Continuous Sandstone-like Structure**: Where sandy elements predominate in volume.
- **Continuous Conglomerate or Breccia-like Structure**: Where coarse elements predominate in volume.

3.4.3. Fragmentary Structure

This is the dominant structure in agricultural soils. It is characterized by the assembly, by a binder, of individual particles into basic structural units called aggregates, spaced sufficiently to allow both infiltration and adequate retention of water needed for vegetation. Additionally, this promotes chemical interactions, thus supporting the proper functioning of nitrogen, carbon, phosphorus, and sulfur cycles: it is the most beneficial structure for agriculture. There are three types of fragmentary structure (table 3, 4):

- Sheet Structure
- Angular Structure
- Spherical Structure.

The spherical structure, including the crumbly structure, is the best structure in terms of agriculture.

Table 3: Types and Classes of Structure.

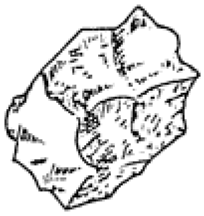
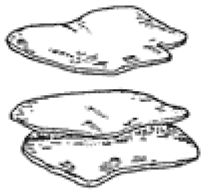
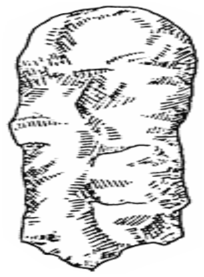
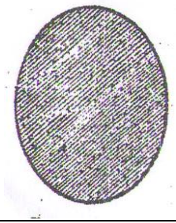
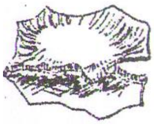
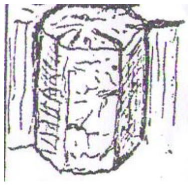
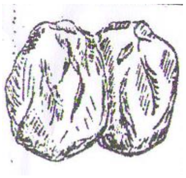
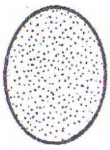
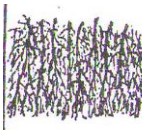
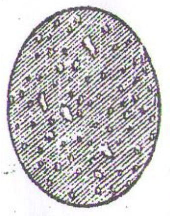
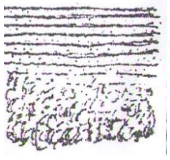
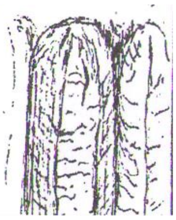
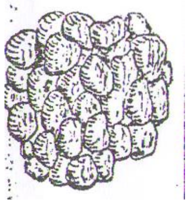
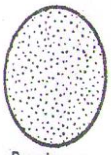
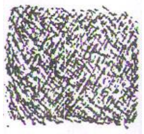
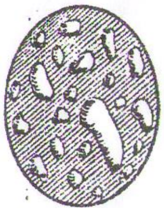
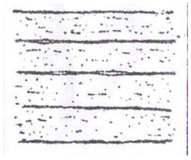
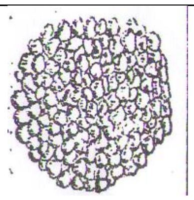
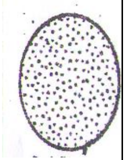
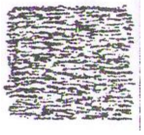
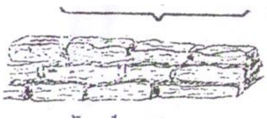
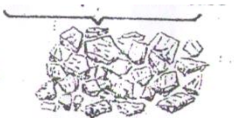
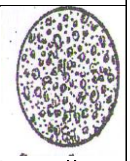
APPEARANCE OF AGGREGATES	STRUCTURE	POROSITY	ROOT PENETRATION
	Polyhedral	Average	Variable
	Granular	High	Good
	Grumeleuse	Very high	Excellent
	Lamellar	Low	Poor, deviated roots
	Prismatic	Low	Roots localized on the surface of prisms

Table 4: Types of Structure.

Continuous or compact	**Fragmentary**			**Particulate**	
	Layered	Angular	Spherical	Mineral	organic
Ciment 	 scaly	prismatic 	 massif	 ashy	 fibrous
Sandstone 	 schistose	columnar 	 nuciform	 powdery	 felted
 Puddingstone	 laminar	 Cubic	 Lumpy/ clumpy	 sandy	 layered
	 Platy  Polyhedral			 Gravelly	
				 Rocky	

3.5. Factors of structure degradation

The deterioration of the structural framework manifests in the field through various phenomena:

3.5.1. Crusting

The impact of raindrops (splash effect) causes the breakdown (breakage) of clods until the appearance and isolation of individual particles. The transport of suspended individual particles and their deposition further away forms a smooth surface, typically a few centimeters thick, called a crust. This crust, acquired after drying, exhibits very strong cohesion, becoming a serious obstacle to fluid transfer and plant emergence.

3.5.2. Mass Swelling

It usually occurs during rainy periods with excessive rainfall and particularly affects the worked (plowed) horizon. After drying, the particles coalesce to form a compact, continuous structure with strong cohesion.

3.5.3. Freeze-Thaw Action

The alternating cycles of freeze and thaw can cause spectacular damage to the soil structure. During the thaw period, water rises from underlying horizons to the still frozen surface horizon. During a wet thaw, the soil is abruptly transformed into mud.

3.5.4. Compaction

Can result from anthropogenic actions (use of soil tillage tools, tires, trampling).

3.6. Factors that Improve Soil Structure

3.6.1. Mineral Amendments

Liming (limestone and gypsum amendments) makes clayey soils more permeable by promoting the flocculation of individual solid particles, making the soil easier to work.

3.6.2. Organic Amendments

Manure, straw, green manure (natural grassland), urban and industrial residues (compost, residual sludge).

3.6.3. Cultural Practices

- Avoid working the soil in excessively wet conditions to prevent possible compaction by machine tires and smoothing by plowing instruments; wait for the soil to dry.
- Avoid working the soil always at the same depth to prevent the creation of a plow sole, detrimental to rooting.
- Plow along contour lines in sloping soils.
- Drain excess water through proper drainage.

3.7. Consequences of Soil Structure

3.7.1. Porosity

3.7.1.1. Introduction

Soil porosity is a function of texture, structure, and the biological activity that develops within it. The larger the textural elements, the larger the voids left between them, unless finer particles simultaneously occupy these voids created by the larger particles, or if these same voids are filled by colloidal cements.

3.7.1.2. Definition of Porosity 1: Soil porosity, also known as pore space or void space, is occupied by the liquid and gaseous phases of the soil. This space can also be used by the roots and microorganisms in the soil.

3.7.1.3. Definition of Porosity 2: Defined as the ratio of the volume of voids to the total volume of the soil (also called the apparent volume), it also characterizes the spaces between soil particles:

$$P\ \% = \frac{Vv}{Vv + Vs}$$

The porosity of agricultural soils ranges from 25% (compacted soils) to 60% (well-aggregated soils, rich in organic matter, with significant biomass).

3.7.1.4. The types of porosity Soil porosity is subdivided into two categories:

3.7.1.4.1. Textural porosity

The pores formed are a result of the arrangement of solid soil particles, and therefore, it is dependent on the soil texture.

3.7.1.4.2. Structural porosity

The origin of the pores is the result of natural or anthropogenic actions that have favored the formation of voids during soil structuring (wetting/drying cycle, plowing, etc.). Two subsets are distinguished within the total porosity:

- **Macroporosity**

Composed of macropores (shrinkage cracks, earthworm burrows, root channels, etc.) through which fluids (water, gases) circulate, and the size of the pores is generally greater than 30µm.

- **Microporosity**

Composed of micropores (small cracks, compaction pores, etc.), where water is stored. The size of micropores is generally less than 8 or 10 µm.

3.7.1.5. Factors Influencing Soil Porosity

All factors and agents that disrupt soil structure have a detrimental effect on soil porosity (compaction, impact of raindrops, trampling, etc.). Similarly, any improvement in soil structure results in an increase in soil porosity, especially in fine-textured soils such as clayey soils. Thus, the addition of organic matter, manure, or flocculation agents (lime), biological activity (work of earthworms and small insects), and plowing all contribute to an increase in porosity.

Chapter 02: Water in the Soil

1. Introduction

The value of soil as a suitable medium for plant growth depends not only on the presence and quantity of chemical nutrients but also on the movement of water and air, as well as the chemical properties and thermal regime of the soil.

Water is an essential component of the soil (15 to 35% by volume). Its role as a carrier of ions in solution and as an essential product for plant life is crucial. Moreover, water plays a significant role in the genesis and evolution of soils.

2. Constituent Phases of Soil

Soil is composed of three phases (Fig. 8, 9, and 10):

2.1. Solid Phase: represented by organic and mineral solid particles.

Organic solid particles consist of plant debris (leaves, small branches), soil fauna (ants, insects, earthworms, snails), etc.

Mineral solid particles consist of gravel, sand, clay, and silt.

2.2. Liquid Phase: represented by water and dissolved mineral elements (soil solution).

2.3. Gaseous Phase: represented by air or the atmosphere of the soil (oxygen, carbon dioxide, nitrogen, etc.) - see Table 5.

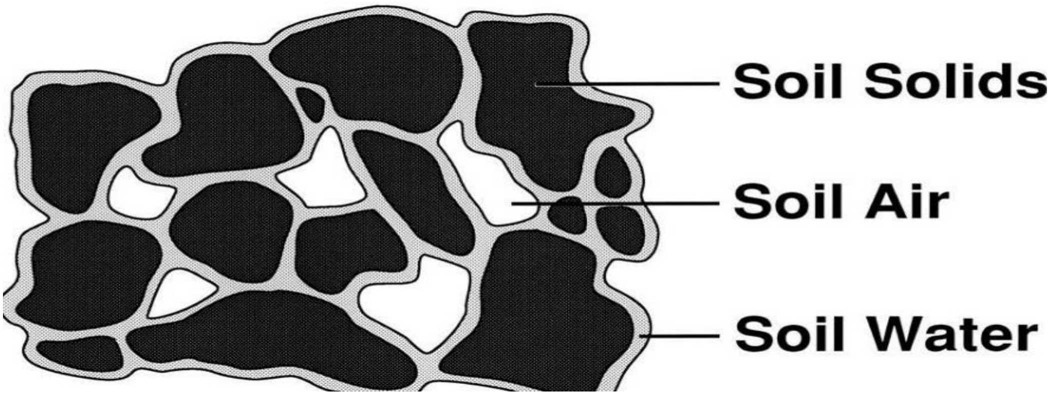


Fig. 8: The Three Phases of Soil.

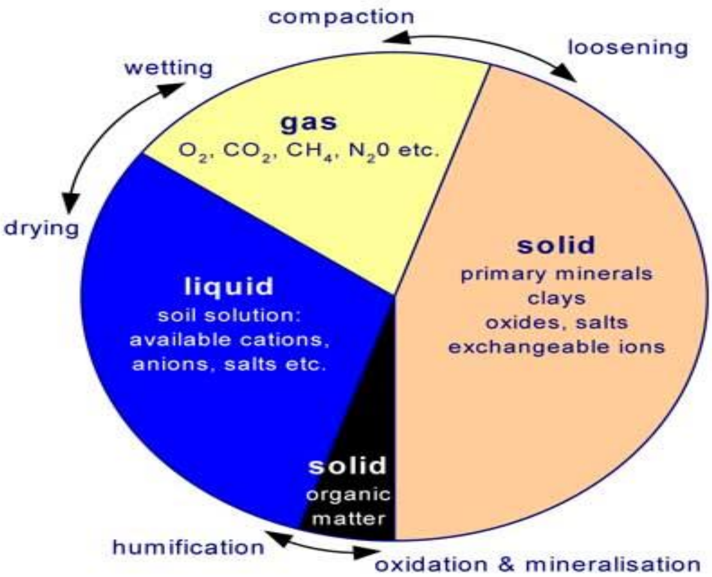


Fig. 9: Average Composition of the Soil.

Table 5: Composition of Soil Air.

Constituant	**Oxygen**	**Nitrogen**	**Carbon Dioxide**	**Water Vapor**	**Diverse Gases**
Soil Air **%**	18-20.5 in well-aerated soil 10 after rain 2 in compacted structure	78.5 à 80	0.2 à 3.5	Generally saturated	Trace of H2, N2O, Ar In anoxia: NH3, H2S, CH4

3. Relationship between the three phases of the soil

In a mass of soil, there are three physical components: solid, water, and air. A phase relationship diagram is normally used to represent the relationship as follows:

Definitions:

Volume: (ft^3, m^3)

- V_t: Total volume
- V_s: Volume of solid
- V_v: Volume of void
- V_w: volume of water
- V_a: Volume of air

Weights: (lbs, kg, kN)

- W_t: total weight
- W_s: weight of solid
- W_w: weight of water
- Weight of air = 0

Phase Relationships:

Volume-volume relationship:

- Void ratio (no unit):

$$e = \frac{V_v}{V_s}$$

- Porosity (no unit):

$$n = \frac{V_v}{V_t}$$

- Degree of saturation (%):

$$S\,(\%) = \frac{V_w}{V_v} * 100$$

- air content:

$$A = \frac{V_a}{V_t}$$

Weight-weight relationship:

- Water (Moisture) content (%):

$$w\,(\%) = \frac{W_w}{W_s} * 100$$

Weight-Volume relationship:

(Unit weight or density, lbs/ft^3, g/cm^3, kN/m^3)

- Moisture (total) unit weight:

$$\gamma_t = \frac{W_t}{V_t}$$

- Dry unit weight:

$$\gamma_d = \frac{W_s}{V_t}$$

- Solid unit weight

$$\gamma_s = \frac{W_s}{V_s}$$

- Saturated unit weight (when soil is completely saturated, S = 100%,V_a=0):

$$\gamma_{sat} = \frac{W_t}{V_t}$$

- Submerged (buoyant) unit weight (when soil is below ground water table, S = 100%):

$$\gamma_b = \gamma_{sat} - \gamma_w$$

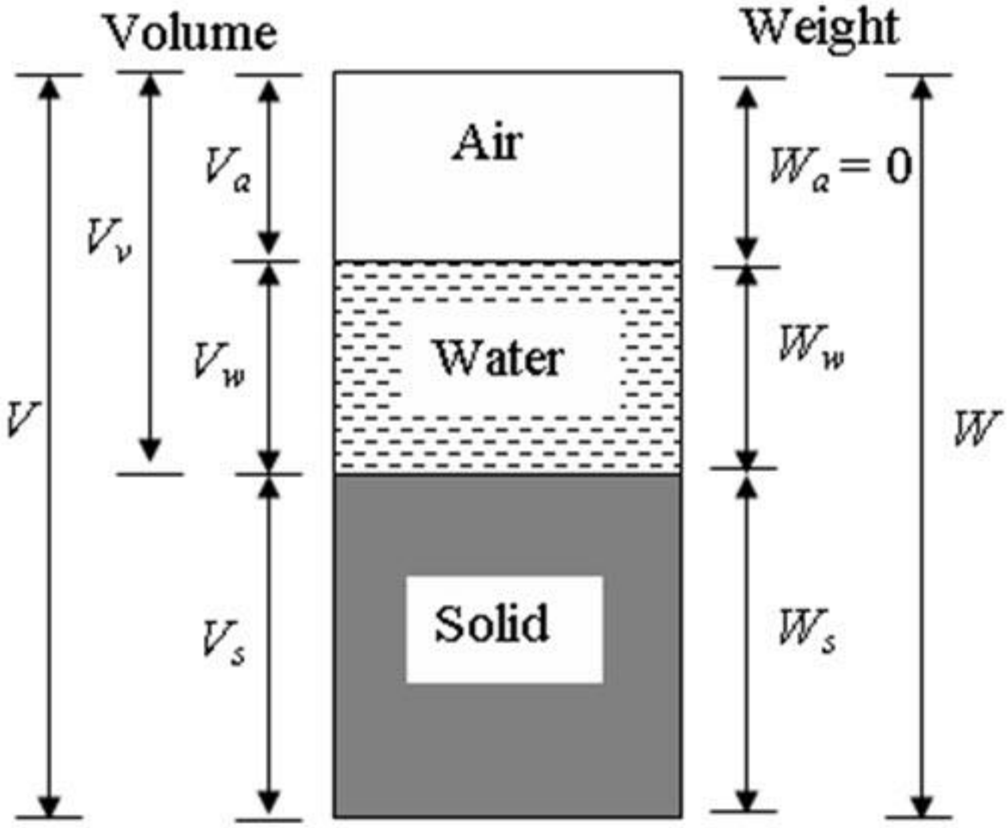


Fig. 10: Diagram illustrating the three phases of the soil.

4. Water States in the Soil

There are three states of water in the soil, distinguished by the force with which it is retained and its availability to plants: gravitational water, water usable by the plant, and water unusable by the plant (fig. 11).

4.1. Gravitational Water

Gravitational water exists in the soil only in the hours or days following precipitation or in the case of a permanent water table.

Gravitational water moves through coarse and medium pores (greater than 10 µm), mostly vertically and sometimes obliquely.

Vertical gravitational water flow can be divided into two parts:

Rapid gravitational flow: water that moves through coarse pores (greater than 50 µm) in the hours following rainfall.

Slow gravitational flow: water that descends slowly (often over several weeks) through medium pores with diameters ranging from 50 µm to 10 µm.

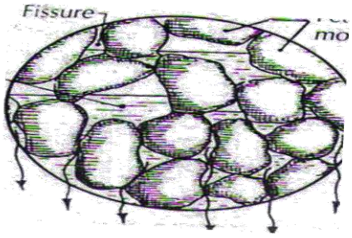
4.2. Water Usable by Plants

This is water retained by the soil, either within fine channels or in the form of relatively thick films around solid elements. It occupies the fine pores with diameters ranging from 0.2 to 50 µm on the surface of particles.

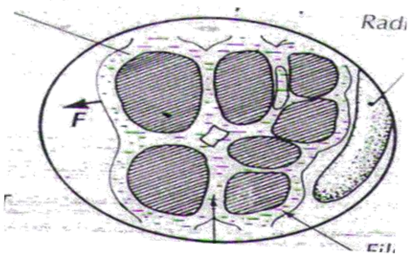
4.3. Water Unusable by Plants

The water forms thin films around solid elements or even fine droplets of condensed water vapor (hygroscopic water). This water, being too energetically retained, cannot be absorbed.

Gravity water



Water available to the plant



Water inaccessible to the plant

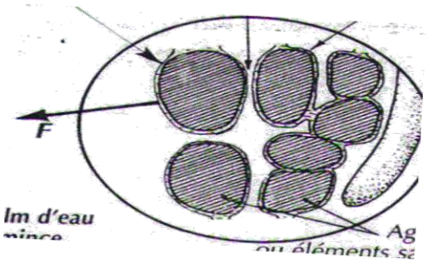


Fig. 11: The Three States of Water in the Soil.

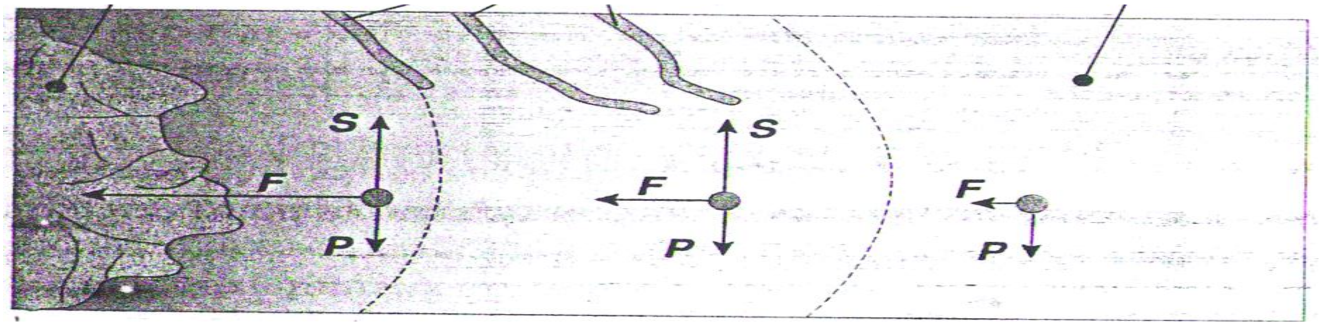
5. Forces Acting on Soil Water

Three forces act on soil water: gravity (P), root suction (S), and soil suction (F) (fig.12).

The water forming variable-thickness films around solid elements experiences a force exerted by the solid on a water molecule. This force is more intense the closer the molecule is to the solid; this is **the force of soil suction**.

- Beyond a certain distance, the attractive force (soil suction) is weaker than gravity: water flows by **gravity.**

When the force of soil suction and the force of gravity equalize, the wilting point, or the moisture content at field capacity, is reached. The plant can utilize water as long as the root suction force is greater than the force exerted by the soil on the water.



Water inaccessible to the plant	Permanent wilting point	Water available to the plant	wilting point	Gravity water
F > S	**F = S**	**F<S**	**F=P**	**S=0**
		F>P		**F<P**
Pores < 0.2 µm		Pores 0.2 -10 µm		Pores 10-50 µm slow drainage. > 50 µm rapid drainage

FIG.12 : Forces acting on soil water.

6. Soil Water Potential

The equilibrium of water in the soil is influenced by gravity, dissolved salts, porosity, and pressure from the gaseous phase. Each of these factors imparts a certain potential energy to water.

6.1. Matric potential

Corresponds to the forces exerted by the solid phase on soil water. It varies with the soil's drying state. To extract water from the soil in different states of wilting and drying, a specific pressure must be applied for each state. The soil's suction force for water is expressed in bars, kilopascals (kPa), centimeters of water, or in pF units.

The soil water potential can range from 0 in saturated soil to 10,000 atmospheres in dry soil. The pF values range from 0 for water only weakly retained by the soil to 7 for water strongly adsorbed on the surface of particles (Table 6).

Table 6: Correspondence of Static Pressure Expressions.

Bars	Kilopascals	Atmospheres	mm of mercury	Equivalent Height in Centimeters of Water	**pF**
0.001	0.1	0.000987	0.75	1.017	0
0.01	1	0.00987	7.50	10.17	1
0.1	10	0.0987	75	103	2
0.33	33	0.328	250	344	**2.5**
0.5	50	0.493	375	511	2.7
1	100	0.9869	750.1	1017.1	3
10	1 000	9.869	7501	10171	4
15	1 500	15.2	11251	15499	**4.2**
100	10 000	98.69	75010	101710	5
1 000	100 000	986.9	750100	1017100	6
10 000	1 000 000	9869	7501000	10171000	7

7. Characteristic Soil Moisture Values

Two values hold particular importance: field capacity and wilting point.

7.1. Field Capacity or Retention Capacity

This refers to the water retained by the soil after a period of rainfall and a subsequent drying period of two or three days. It can be measured in the field on soil pre-saturated with water, after 48 hours of drying, using a tensiometer.

However, for poorly permeable soils, drying may take a very long time, sometimes more than 10 to 15 days. Therefore, it is determined in the laboratory using methods such as the pressure membrane apparatus (Richard's pot), centrifugation, or Bouyoucos method (Buchner funnel).

7.2. Wilting Point Moisture

This corresponds to the critical value of bound water, which is non-absorbable by the roots. It can be measured either by the biological method (measuring soil moisture when the plant wilts) or in the laboratory using the pressure membrane apparatus or centrifugation.

8. Available water

This is the amount of water stored in the soil after a period of rainfall, given by the difference between the retention capacity and the wilting point. It can be expressed as a percentage or, more accurately, in millimeters, which allows for comparisons with rainfall and evapotranspiration, also expressed in millimeters.

RU% = Moisture content at field capacity - Moisture content at wilting point
RU mm = (Moisture content at field capacity - Moisture content at wilting point) x bulk density x Depth.
da: Bulk density in g/cm^3
P: Depth in dm.

Soil texture has a direct influence on moisture rates at field capacity and wilting point (and consequently on RU), as shown in the graph on the right (Figure 13):

- Sandy soils have low water retention capacities, resulting in lower RU.
- Soils with a high proportion of fine particles (silt and clay) store more water; however, a significant portion of these water reserves remains unavailable to plants.

Other important points:

- Coarse elements (soil elements with a size greater than 2 mm: stones, gravel, etc.) do not allow for water storage. Soils with a high proportion of coarse elements consequently have limited RU.
- Organic matter has higher retention capacities than clays. However, they release water less easily. The overall impact of organic matter additions is positive on RU, making them beneficial in dryland farming.

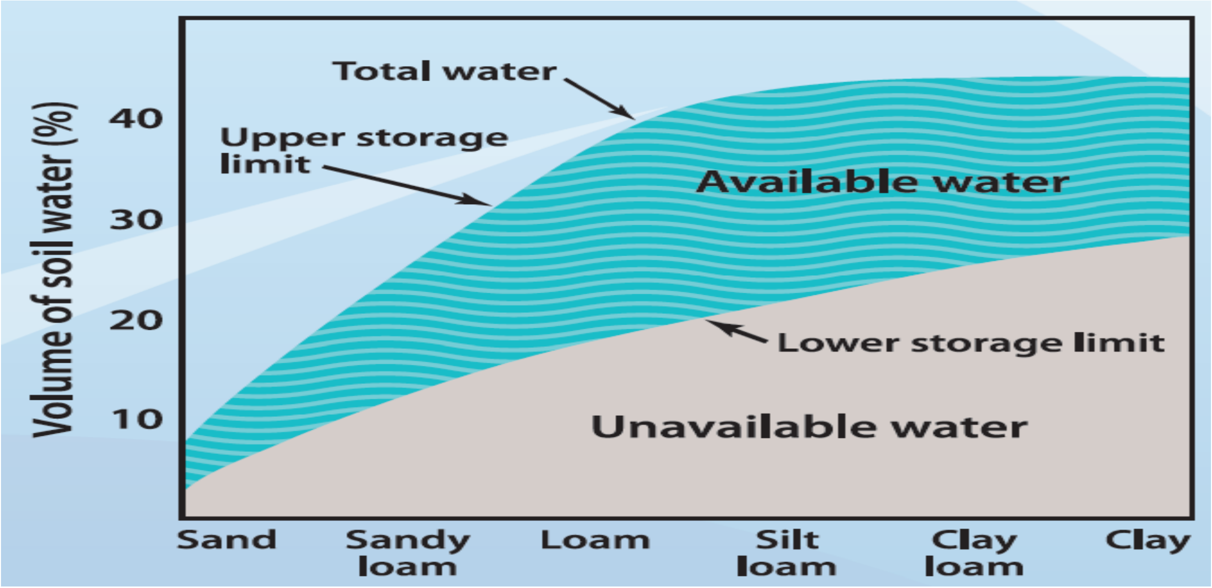


Figure 13: Water Content in the Soil According to Its Texture.

9. Water Movements in the Soil

Water movements in the soil involve two opposing processes: downward movements and upward movements of water.

9.1. Downward Movements of Gravity Water (Permeability)

Downward movements of gravity water, which infiltrates after rainfall and is related to the permeability of the profile. Permeability depends on texture but especially on structure. Permeable soils include:

- Coarse-textured soils dominated by sands and gravels with few colloids.
- Fine-textured soils with fragmentary, especially crumbly, structure.

Impermeable soils include:

- Fine-textured soils, very rich in silt but poor in clay and humus.
- Soils predominantly clayey, especially in the absence of limestone and humus.

9.2. Upward Movements

Water moves from a moister point to a drier point. For example, when the soil is supplied from a more or less deep water table, water moves from the water table to the surface and is capable of constantly rehydrating levels dried out by roots or evaporation.

10. Soil Water Balance

10.1. Definition

The soil water balance represents the quantity of water the soil can contain over time (monthly or ten-day balance). Its quantities are determined by comparing the inputs and outputs of water from the soil-plant-atmosphere system (Fig. 14).

10.2. Water Inputs

- Precipitation: recorded by meteorological stations,
- Irrigation,
- Secondary precipitation (dew, fog),
- Capillary rise.

10.3. Water Outputs

- **Evapotranspiration**: evaporation from bare surfaces + plant transpiration,
- **Drainage**: the amount of water leaving the root zone through infiltration,
- **Runoff**: depends on soil permeability, slope, and precipitation intensity.

11. Potential Evapotranspiration (PET)

Theoretically, it is the maximum amount of water that the atmosphere receives through plant transpiration and soil evaporation. PET is a climatic measure calculated from meteorological data using the Turc formula. Monthly PET (mm) = 0.4 (Ig + 50) T / (T + 15) Where: Ig: Monthly (or ten-day) average value of global solar radiation cal/cm2/day T: Monthly (or ten-day) average temperature 0.4: Coefficient used for calculating monthly PET (replace it with 0.13 for ten-day PET).

12.Actual Evapotranspiration (AET)

Corresponds to soil evaporation and crop transpiration. It is supplied with soil water reserves and precipitation, and its water needs may not be fully met.

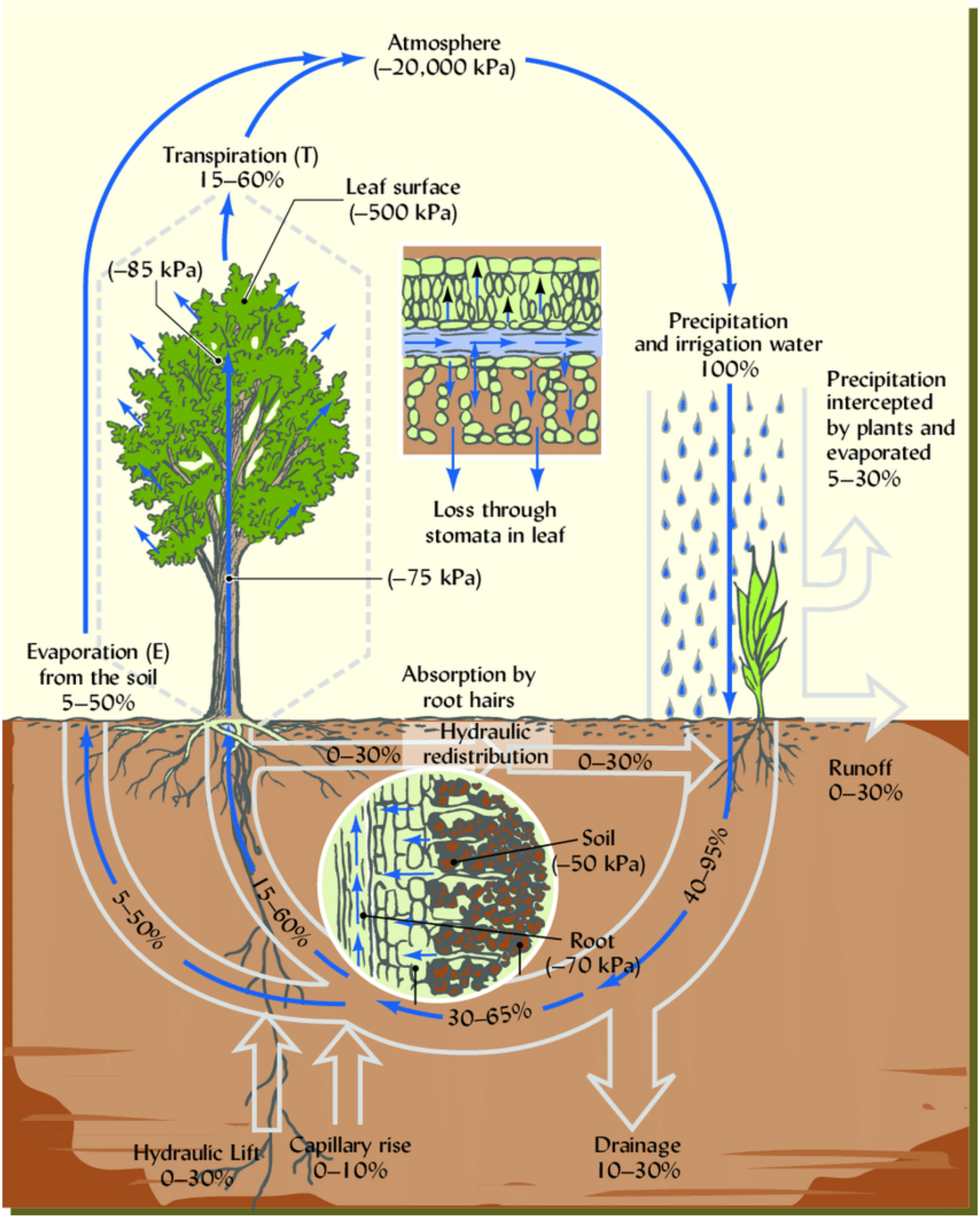


Fig.14 : Soil-plant atmosphere continum showing water movement from soil to plants to the atmosphere and back to the soil.

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