La-Net

AGE 202

INTRODUCTION TO SOIL SCIENCE

Course code: AGE 202

Course title: Introduction to Soil Science

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Series 1: Origin and Formation of Soils

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Introduction

Soil is the thin layer of material covering the Earth's surface that supports plant life, filters water, cycles nutrients, and sustains the ecosystems on which agriculture depends. Yet soil is not simply ground-up rock: it is the product of millions of years of interaction between geological, climatic, biological, and topographic forces, and it continues to form and change today. Understanding how soils originate and develop is the foundation for everything else in soil science — from reading a soil profile in the field to selecting the right management practice for a specific soil type.

The aim of this Series is to introduce you to the nature and importance of soil, the five major soil-forming factors, the processes by which those factors transform parent material into soil, and the concept of the soil profile as the record of soil formation and the primary tool for field soil description and classification.

We shall commence this Series by examining what soil is and why it matters. Next, we will study the five factors that control soil formation. Following that, we will cover the weathering, transformation, and organic matter processes that build soil. Finally, we will wrap up with the soil profile — its horizons, their characteristics, and how to describe a profile in the field.

Series Learning Outcomes

Upon completing this Series, you should be able to:

- **SLO 1.1** define soil and explain its importance to agriculture and the environment (Linked to Part 1.1),
- **SLO 1.2** identify and describe the four major components of soil (Linked to Part 1.1),
- **SLO 1.3** explain how soil functions as a dynamic natural system (Linked to Part 1.1),
- **SLO 1.4** describe the five soil-forming factors and explain the role of each in determining soil properties (Linked to Part 1.2),
- **SLO 1.5** explain physical and chemical weathering processes and their role in soil formation (Linked to Part 1.3),
- **SLO 1.6** describe the processes of transformation, translocation, and accumulation in the soil profile (Linked to Part 1.3),

- **SLO 1.7** explain humification and the role of organic matter incorporation in soil formation (Linked to Part 1.3),
- **SLO 1.8** define the soil profile and describe the major soil horizons and their characteristics (Linked to Part 1.4), and
- **SLO 1.9** conduct and record a basic soil profile description in the field (Linked to Part 1.4).

1.1 The Nature and Importance of Soil

1.1.1 Definition and importance of soil

Soil is the naturally occurring, unconsolidated surface layer of the Earth that has been altered by physical, chemical, and biological processes to support plant growth. It differs from the underlying parent rock or unweathered geological material by having a distinct composition, structure, and biological community. The definition of soil in the pedological (soil science) sense emphasises its role as a medium for plant growth; in the engineering sense, soil refers more broadly to any loose surface material regardless of biological activity.

The importance of soil to human society is difficult to overstate. It is the foundation of food production, supporting 95 per cent of global food supply through crop and animal production. It is the primary water filter and reservoir, purifying water as it percolates through the soil profile and releasing it slowly to streams and aquifers. It cycles carbon, nitrogen, phosphorus, and other nutrients, regulating the chemical composition of the atmosphere and water. It provides physical support for infrastructure and buildings. And it is a reservoir of biodiversity, containing approximately a quarter of all living species on Earth. Soil degradation, through erosion, salinisation, compaction, and pollution, is one of the most serious environmental challenges facing Nigeria and the world.

Fill in the blank: Soil is the naturally occurring, unconsolidated ________ layer of the Earth that has been altered by physical, chemical, and biological processes to support plant growth.

Figure 1.1: Diagram showing the multiple roles of soil in food production, water filtration, nutrient cycling, and biodiversity support

1.1.2 Components of soil

Soil is composed of four major components whose relative proportions determine most of its physical and chemical properties. **Mineral matter** (typically 45 per cent of the volume of a typical agricultural soil) consists of weathered rock and mineral particles of varying sizes (sand, silt, and clay); it provides the structural framework of the soil and is the primary reservoir of most plant nutrient elements. **Organic matter** (approximately 5 per cent) consists of living organisms, fresh plant residues, and decomposed humus; it profoundly influences soil fertility, structure, and water-holding capacity despite its small proportion.

Soil water (approximately 25 per cent) occupies the pore spaces between solid particles; it is the medium through which dissolved nutrients are transported to plant roots and through which most chemical reactions in the soil occur. **Soil air** (approximately 25 per cent) also occupies pore spaces; it provides the oxygen required for root respiration and aerobic soil microorganism activity. The proportions of water and air are inversely related and vary constantly with rainfall, drainage, and plant uptake. The mineral and organic fractions are relatively stable over time, while water and air contents are highly dynamic.

Fill in the blank: The four components of a typical agricultural soil are mineral matter (45%), organic matter (5%), soil ________ (25%), and soil air (25%).

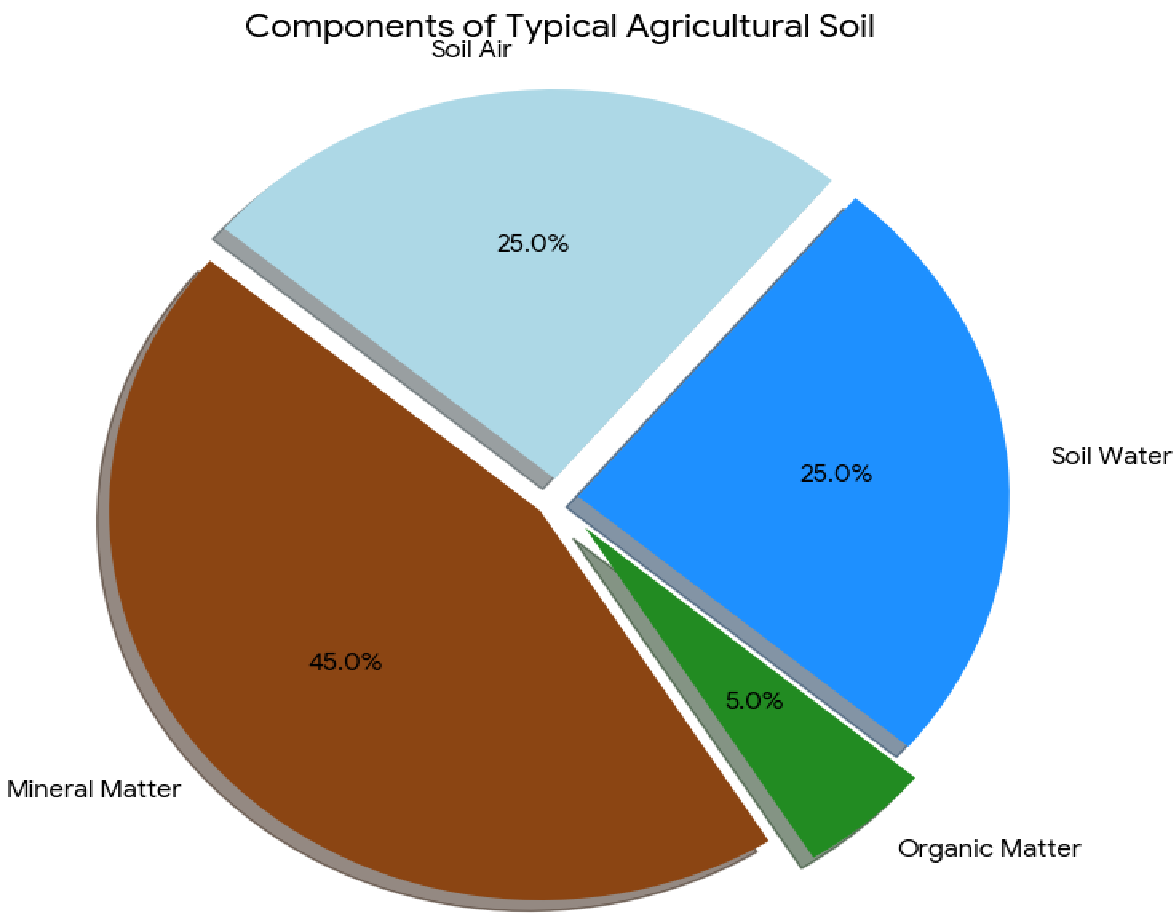

Figure 1.2: Pie chart or diagram showing the four components of a typical agricultural soil by volume percentage

1.1.3 Soil as a dynamic system

Soil functions as a dynamic natural system — a continuously changing body in which physical, chemical, and biological processes interact and influence one another. Energy inputs (solar radiation, rainfall) drive the physical and chemical weathering processes that release mineral nutrients. Biological activity (plant root growth, microbial decomposition, earthworm burrowing) transforms organic materials, creates pore structure, and mediates nutrient cycling. Chemical reactions (mineral dissolution, ion exchange, precipitation, oxidation-reduction) control the availability of nutrients and toxic elements.

The dynamic nature of soil means that its properties respond to management: tillage changes soil structure; organic matter additions improve fertility and water retention; drainage alters the chemical environment; and erosion removes the most fertile surface horizons. This responsiveness to management is both the opportunity and the challenge of soil science — soils can be degraded rapidly through poor management but can also be improved through informed intervention. Understanding the interconnected processes operating in the soil system is essential for making management decisions that sustain productivity without long-term degradation.

Fill in the blank: Soil functions as a ________ natural system in which physical, chemical, and biological processes interact continuously and respond to environmental inputs and management practices.

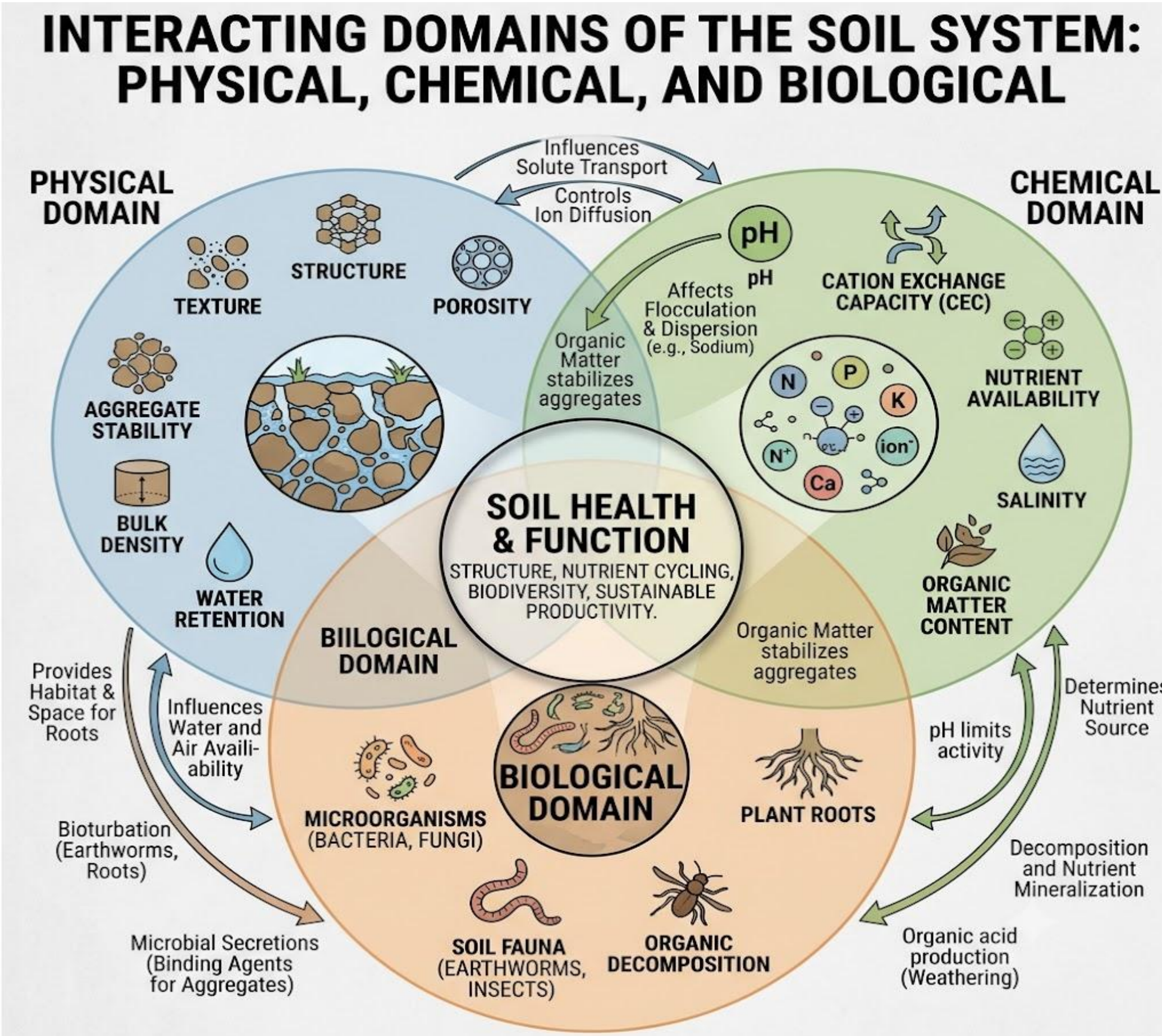

Figure 1.3: Diagram showing the interactions between the physical, chemical, and biological components of the soil system

Pilot questions 1.1

1. Define soil in the pedological sense and explain how it differs from unweathered parent material.
2. State four roles of soil in the natural environment and explain the significance of each.
3. Name the four components of a typical agricultural soil and state their approximate percentage volumes.
4. Explain why soil water and soil air are considered inversely related.
5. Explain what is meant by describing soil as a dynamic natural system.

1.2 Soil-Forming Factors

1.2.1 Parent material

Parent material is the unconsolidated geological material from which soil is formed. It may be the underlying bedrock (in situ parent material) that weathers in place, or transported material deposited by water (alluvium), wind (aeolian deposits or loess), ice (glacial till), or gravity (colluvium). The mineralogical and chemical composition of the parent material has a profound influence on the resulting soil: soils formed from basic igneous rocks (basalt, dolerite) rich in calcium, magnesium, and iron tend to be fertile with neutral to slightly acidic pH, while soils formed from acidic igneous rocks (granite) or siliceous sedimentary rocks (sandstone) tend to be sandy, nutrient-poor, and strongly acidic.

The physical texture of the parent material also influences soil development: coarse-grained parent materials (sands, gravels) weather to produce sandy soils with rapid drainage; fine-grained parent materials (shales, mudstones, clays) produce clay-rich soils with poor drainage. In Nigeria, the major parent materials include crystalline basement complex rocks (granite, gneiss, schist) in the north and middle belt, sedimentary rocks (sandstone, shale, limestone) in the south and east, and coastal alluvial deposits in the Niger Delta. Each parent material type produces distinctive soils with different agricultural potential.

Fill in the blank: ________ material is the unconsolidated geological material from which soil is formed, and its mineral composition strongly influences the fertility and pH of the resulting soil.

Parent Material	Mineralogy	Weathering Products	Typical Soil Properties
Basalt	Rich in pyroxene, olivine, plagioclase	Clay minerals (smectite, montmorillonite), Fe oxides	Dark, fertile soils; high shrink-swell; good nutrient supply
Granite	Quartz, feldspar, mica	Sandy soils, kaolinite, coarse fragments	Light-textured, acidic soils; low fertility; well-drained
Sandstone	Mostly quartz, minor feldspar	Coarse sand, resistant quartz grains	Sandy soils; low water-holding capacity; poor fertility

Alluvium	Mixed minerals depending on source rocks	Variable clays, silts, sands	Fertile, stratified soils; good moisture retention; widely farmed
Shale	Fine-grained clay minerals, quartz, carbonates	Clay-rich soils, kaolinite, illite	Heavy, poorly drained soils; prone to compaction; moderate fertility

Table 1.1: Common parent materials, their mineral composition, and the typical soil properties they produce

1.2.2 Climate and organisms

Climate is the most powerful soil-forming factor over broad geographic regions. Temperature controls the rate of chemical weathering (reaction rates roughly double for every 10°C increase in temperature) and biological activity (both slow dramatically at low temperatures). Rainfall determines the water available for weathering, leaching of soluble materials, and the hydration reactions of clay mineral formation. High rainfall combined with high temperature, as in Nigeria's forest zones, accelerates weathering, promotes deep soil development, and leads to intense leaching of bases (calcium, magnesium, potassium) producing acidic, highly weathered soils (Oxisols). Dry climates produce less weathered, more fertile soils.

Organisms — plants, animals, and microorganisms — are biological soil-forming agents. Plants contribute organic matter through root turnover and leaf litter, creating the surface organic horizon; root channels create macropores for water and air movement; root exudates drive chemical weathering in the rhizosphere. Microorganisms (bacteria, fungi, actinomycetes) decompose organic matter, cycle nutrients, and drive nitrogen fixation. Larger organisms such as earthworms and termites mix soil horizons, improve soil structure, and create channels. In tropical Africa, termite activity is a major pedogenic process, constructing mounds that elevate and redistribute soil materials over large areas.

Fill in the blank: ________ is considered the most powerful soil-forming factor over broad geographic regions because it controls both the rate of chemical weathering and the intensity of leaching.

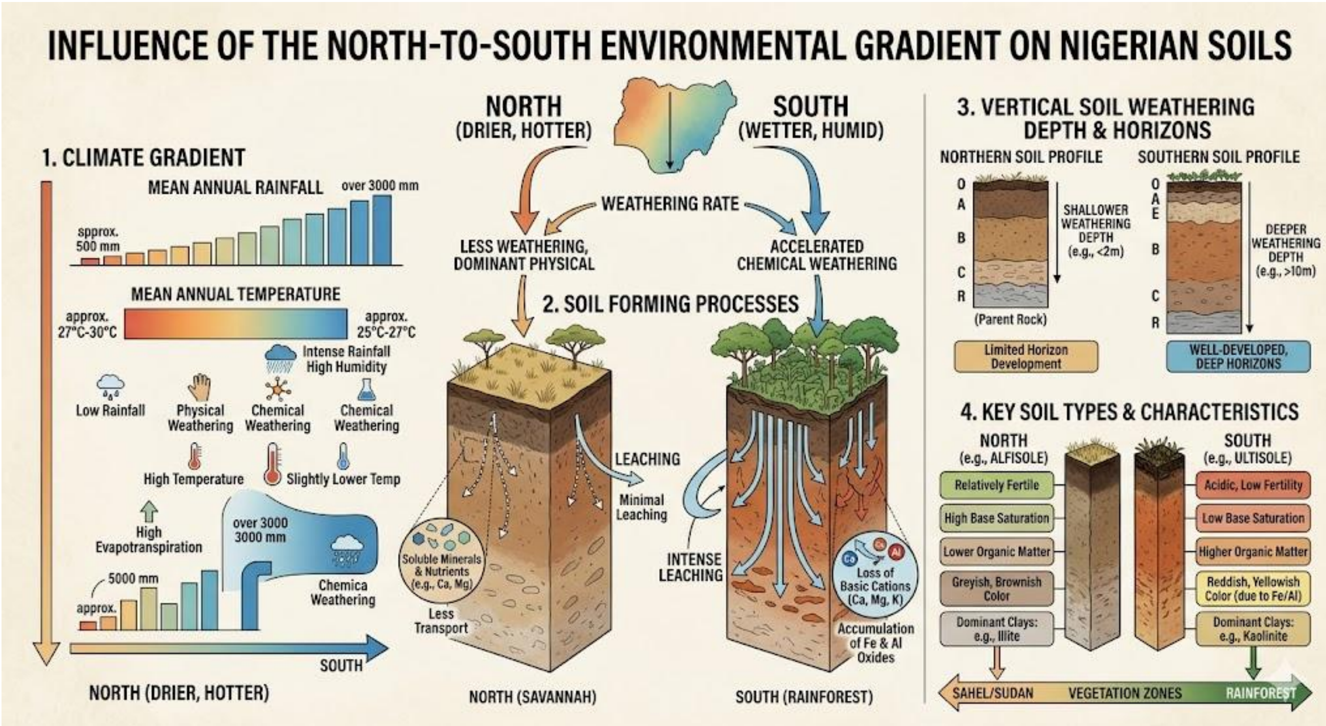

Figure 1.4: Diagram showing the influence of climate on soil formation along a rainfall and temperature gradient in Nigeria

1.2.3 Topography and time

Topography (relief) influences soil formation by controlling the redistribution of water, organic matter, and eroded soil material across the landscape. On upper slopes and ridge crests, water drains away rapidly, leaching is limited in depth but lateral flows can remove soluble materials, soils tend to be shallow and well-drained. On lower slopes and valley bottoms, water accumulates from upslope areas, soils are wetter, deeper, and richer in accumulated organic matter and soluble materials. This topographic influence on soil properties is called the catena or toposequence — the systematic change in soil properties across a landscape from ridge to valley.

Time is a passive soil-forming factor that allows the other factors to exert their cumulative effects. Young soils (developed on recently deposited alluvium, volcanic ash, or glacial deposits) show little horizon development and closely resemble their parent material. Old soils (in tropical Africa, some soils have been forming for millions of years under relatively stable conditions) are deeply weathered, have lost most soluble nutrients through leaching, and have distinctive red and yellow colours from iron oxide accumulation. The soils of the Nigerian basement complex are among the oldest on Earth and show the properties of extreme weathering: low inherent fertility, dominance of kaolinite clay, and deep red to yellow lateritic profiles.

Fill in the blank: The systematic change in soil properties from ridge top to valley bottom due to topographic control of water redistribution is called a catena or ________.

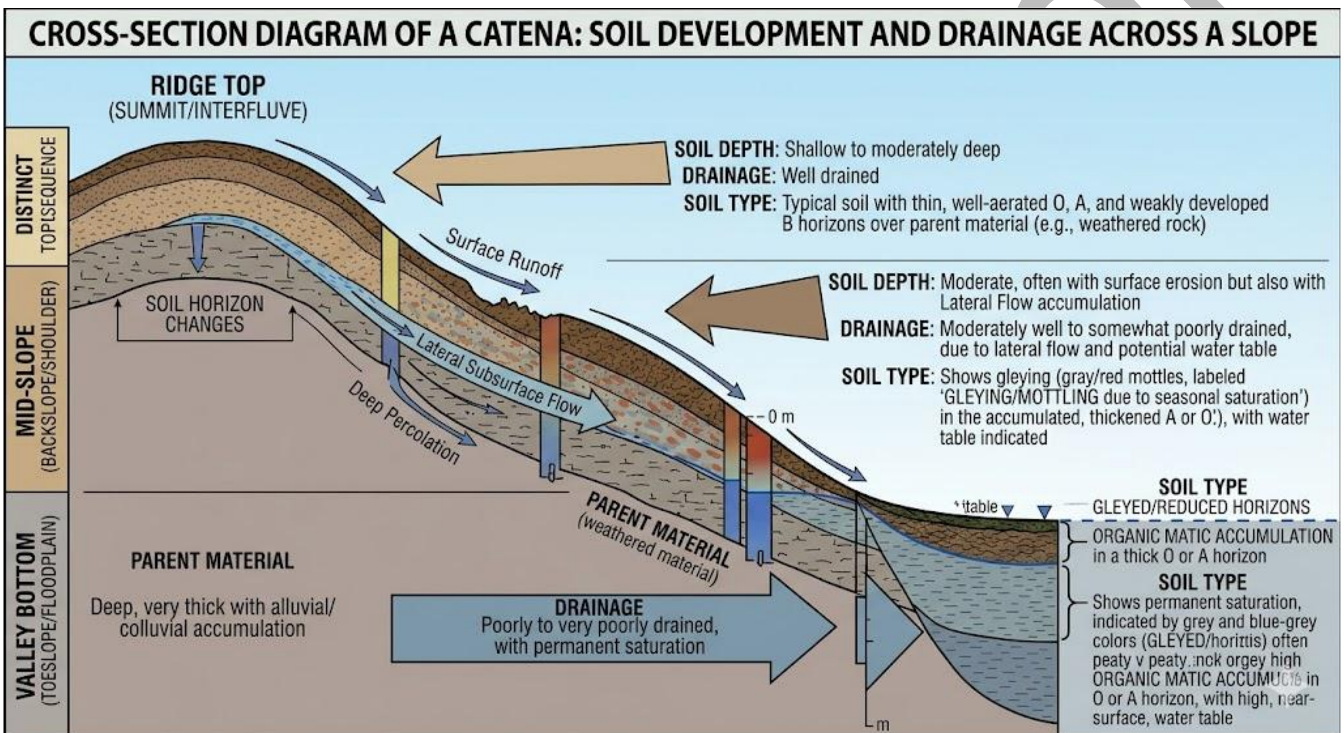

Figure 1.5: Diagram showing a catena (toposequence) with soil profile changes from ridge to valley bottom

Pilot questions 1.2

1. Define parent material and give two examples of transported parent materials found in Nigeria.
2. Explain how the mineral composition of parent material influences the resulting soil's fertility and pH.
3. Explain why climate is considered the most powerful soil-forming factor at the regional scale.
4. Describe two ways in which organisms contribute to soil formation.
5. Explain what a catena is and how topography influences soil properties across a landscape.

1.3 Soil-Forming Processes

1.3.1 Weathering of rocks and minerals

Weathering is the physical disintegration and chemical decomposition of rocks and minerals at or near the Earth's surface under the influence of atmospheric agents (water, oxygen, carbon dioxide, temperature). **Physical weathering** (mechanical disintegration) breaks rock into smaller fragments without changing its chemical composition. Processes include: thermal expansion and contraction (heating and cooling cycles fracture rock surfaces), freeze-thaw action (water expands on freezing and wedges rock apart — less important in Nigeria's tropical climate), root wedging (plant roots penetrate cracks and enlarge them), and abrasion (rock particles worn against each other by water or wind action).

Chemical weathering decomposes rock minerals by altering their chemical composition through reactions with water and dissolved gases. The most important chemical weathering processes are hydrolysis (the reaction of minerals with water; the dominant weathering process for silicate minerals, producing clay minerals and releasing cations), oxidation (the reaction of iron and manganese-containing minerals with oxygen, producing red and yellow iron oxides that are characteristic of many Nigerian soils), carbonation (the reaction of carbonate minerals with carbonic acid from dissolved CO_2 in rainwater, dissolving limestone and forming bicarbonate ions), and hydration (the addition of water to a mineral structure, causing swelling and structural change). In Nigeria's warm, humid forest zone, chemical weathering is intense and soils are deeply weathered.

Fill in the blank: ________ is the dominant chemical weathering process for silicate minerals, producing clay minerals and releasing cations from the mineral lattice into the soil solution.

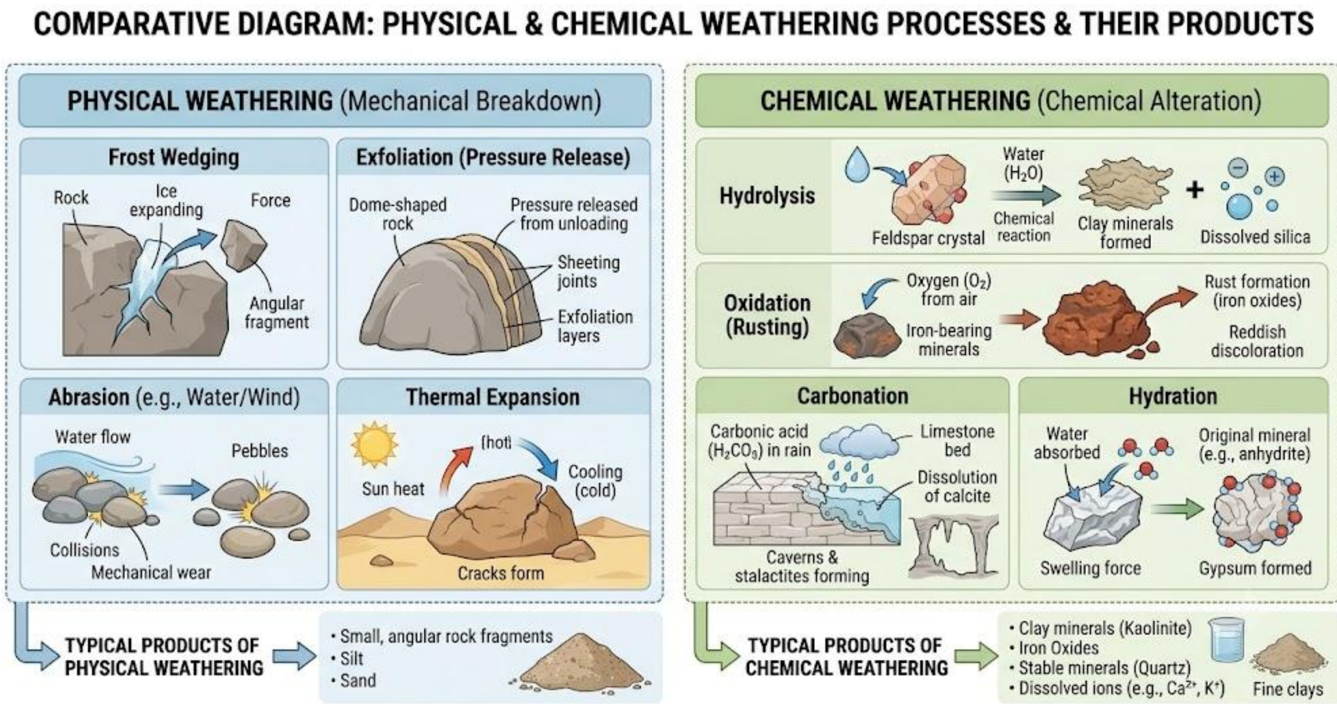

Figure 1.6: Diagram showing the main physical and chemical weathering processes and their products

1.3.2 Transformation, translocation, and accumulation

Transformation refers to the in-place alteration of materials within the soil: primary minerals (feldspars, micas, pyroxenes) are chemically weathered to secondary minerals (clay minerals, iron oxides); organic residues are decomposed by microorganisms and transformed into humus; and new mineral compounds are precipitated from soil solution (calcium carbonate, iron-manganese nodules). Transformation is the basis of all soil development and is driven by the weathering processes described above.

Translocation is the movement of materials from one part of the soil profile to another, carried by water or in suspension. Leaching carries soluble ions (calcium, magnesium, potassium, sodium, nitrate) downward with percolating rainwater, impoverishing upper horizons and enriching lower horizons or groundwater. Clay translocation (lessivage) moves fine clay particles from the A horizon downward to accumulate in the B horizon, forming a clay-enriched argillic horizon. Accumulation (illuviation) is the deposition of translocated materials in a lower horizon:

clay accumulation forms argillic horizons; iron and aluminium accumulation forms spodic horizons; carbonate accumulation forms calcic horizons. Together, transformation, translocation, and accumulation create the distinctive horizons of the soil profile.

Fill in the blank: The downward movement of fine clay particles from the upper horizon to accumulate in a lower argillic horizon is called clay ________ or lessivage.

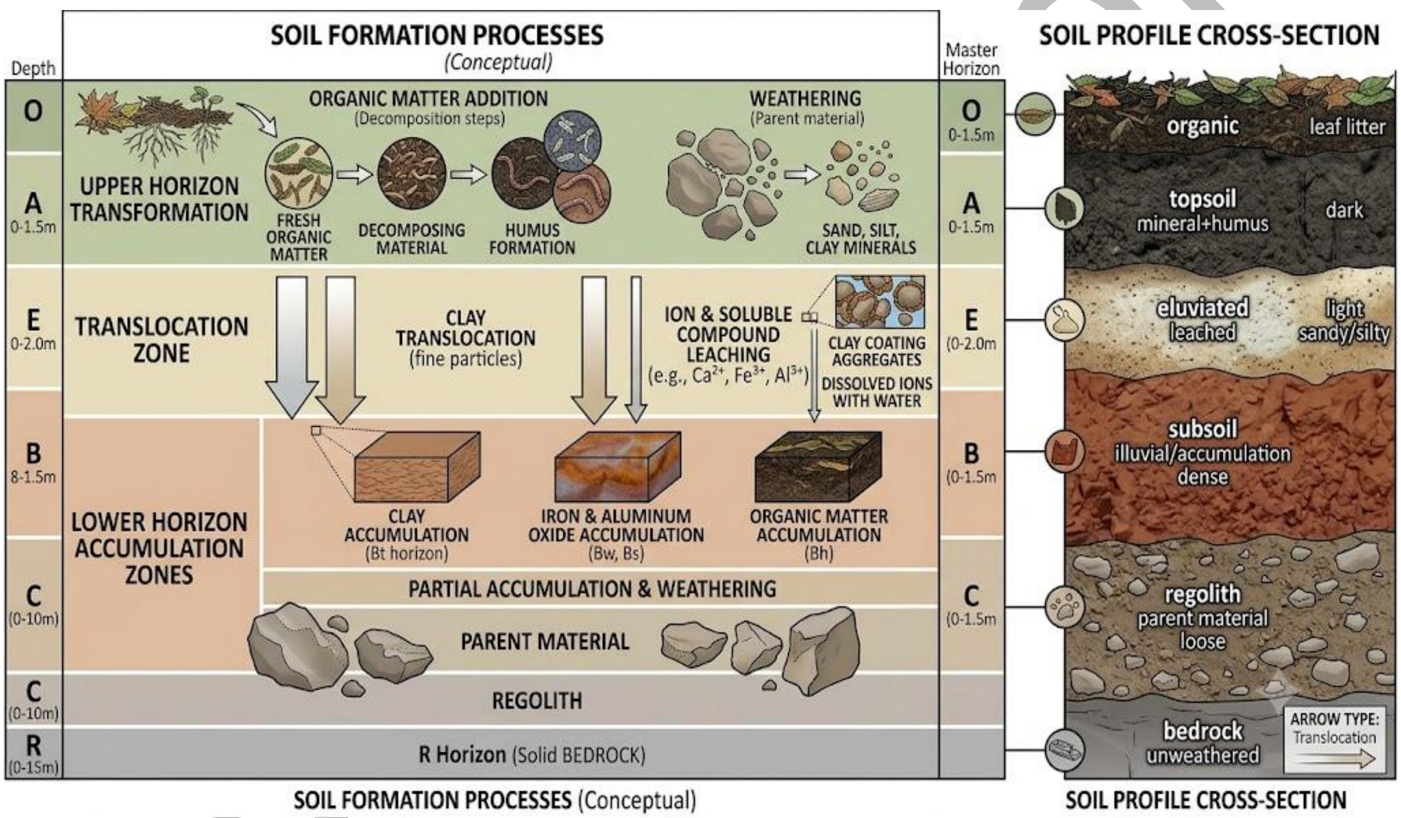

Figure 1.7: Diagram showing the processes of transformation, translocation, and accumulation in a soil profile

1.3.3 Humification and organic matter incorporation

Humification is the biological transformation of fresh organic residues (plant litter, root material, animal matter) into the stable, dark-coloured, complex organic polymer known as humus. The process proceeds in several stages: freshly deposited organic material is colonised by bacteria and fungi that break down easily decomposable components (sugars, proteins, starches); the resistant structural components (cellulose, lignin) decompose more slowly and are transformed through complex biochemical reactions into humic substances — large, dark, acidic, high molecular weight polymers that are resistant to further rapid decomposition.

Humus is critically important to soil fertility and physical properties: it supplies nutrients slowly as it mineralises; it forms stable aggregates with clay particles (organo-mineral complexes) that improve soil structure; it greatly increases the water-holding capacity of the soil; it provides cation exchange sites that retain plant-available nutrients against leaching; and it gives the surface horizon its characteristic dark colour. The incorporation of organic matter into the mineral soil by earthworms, burrowing insects, and physical mixing creates the A horizon — the biologically active, dark, organic-rich surface layer that is the most productive part of the soil profile and the first to be lost by erosion.

Fill in the blank: ________ is the biological transformation of fresh organic residues into the stable, dark-coloured, complex organic polymer called humus through the progressive activity of bacteria and fungi.

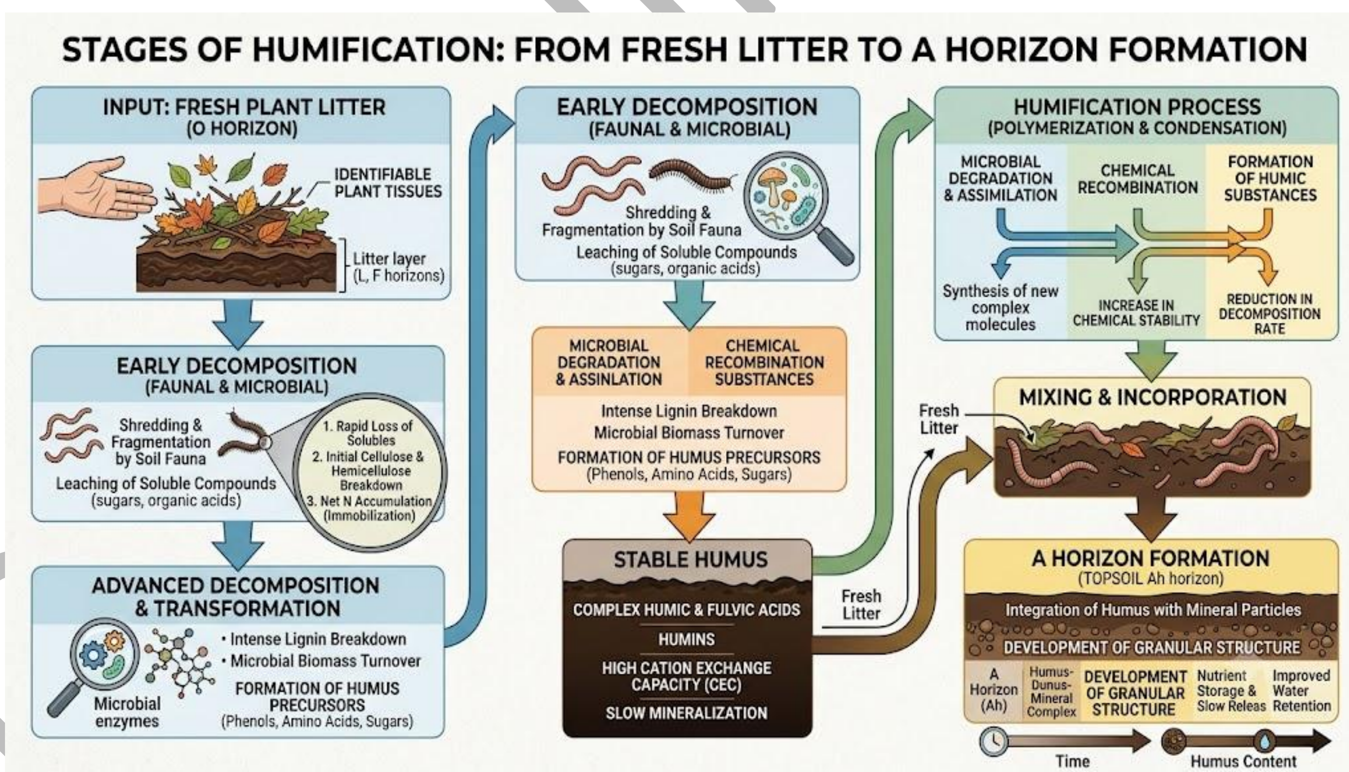

Figure 1.8: Diagram showing the stages of humification from fresh plant litter to stable humus and its incorporation into the A horizon

Pilot questions 1.3

1. Distinguish between physical weathering and chemical weathering and give two examples of each.
2. Explain the process of hydrolysis and state why it is the most important chemical weathering process for silicate minerals.
3. Explain the difference between translocation and accumulation in soil profile development.
4. Define humification and describe the stages through which fresh organic matter is transformed into humus.
5. Explain how humus improves soil fertility and physical properties.

1.4 The Soil Profile

1.4.1 Concept of the soil profile and horizons

The soil profile is the vertical cross-section of the soil from the surface down to the underlying parent material, exposed by digging a soil pit or cutting a road bank. It is the fundamental unit of soil study and the basis for soil classification. The profile reveals the history of the soil — the processes that have acted upon the parent material and the consequences of those processes in the form of distinct horizontal layers called **soil horizons**. Each horizon has characteristic colour, texture, structure, and chemical properties that reflect its formation history.

Soil horizons are distinguished from one another and from the parent material by differences in colour, texture, structure, consistence, and chemical composition that result from the pedogenic processes (weathering, translocation, organic matter accumulation) described in Part 1.3. A soil pit dug to a depth of 1.5 to 2.0 metres typically exposes all the major horizons of a developed soil. The vertical sequence of horizons from the surface to the parent material is the soil profile; different soils in the same region may share similar profiles, forming the basis for soil series and classification systems. The soil profile concept was first systematically developed by the Russian pedologist V.V. Dokuchaev in the 1880s and remains the foundation of modern soil science.

Fill in the blank: The soil ________ is the vertical cross-section from the surface to the parent material, composed of distinct horizontal layers called horizons that reflect the history of pedogenic processes.

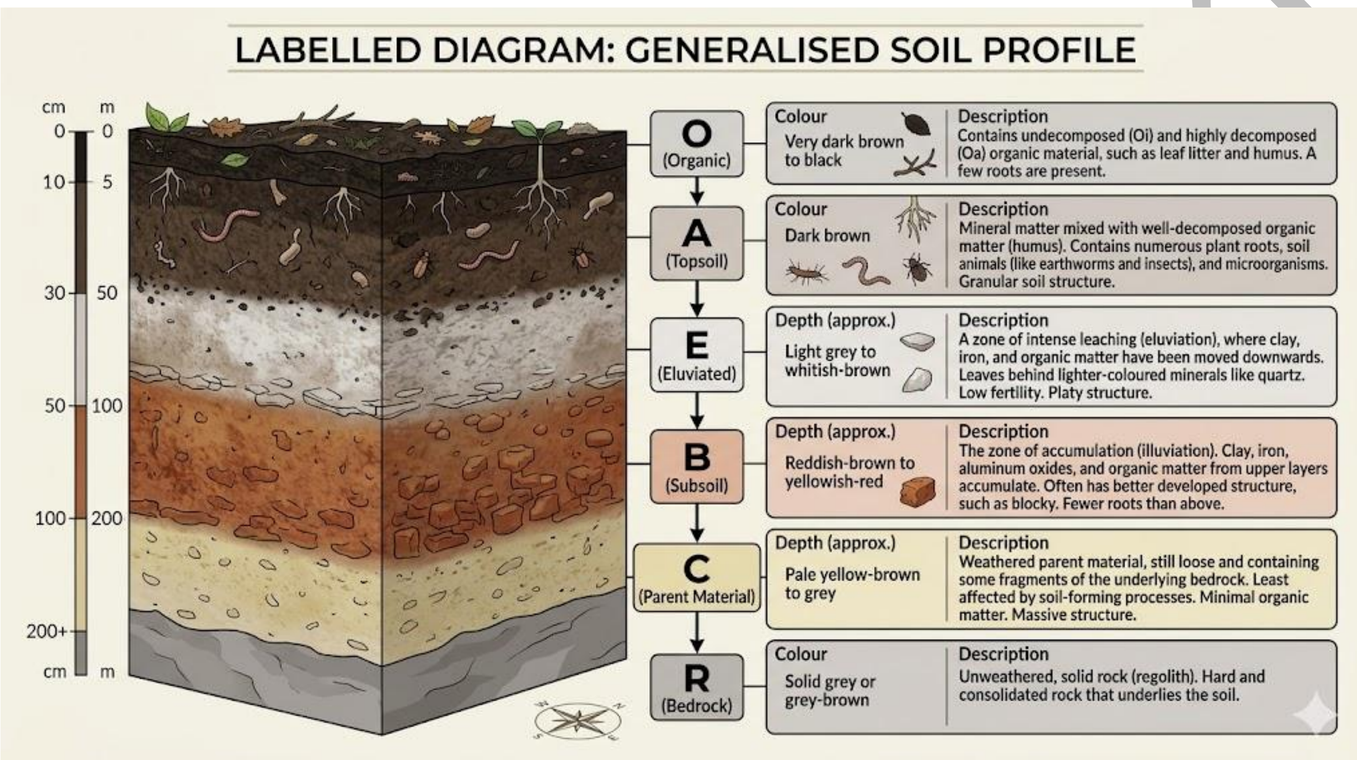

Figure 1.9: Diagram of a generalised soil profile showing the major horizon designations from the surface to the parent material

1.4.2 Description and characteristics of major soil horizons

The O horizon is the organic surface horizon formed by the accumulation of plant litter and partially decomposed organic matter above the mineral soil; it is most prominent in forested soils and is largely absent in cultivated soils where it is incorporated by tillage. The **A horizon** is the topsoil — the uppermost mineral horizon enriched with organic matter (giving it a darker colour than deeper horizons), biologically active, and generally the most fertile layer of the mineral soil. The **E horizon** (eluviation horizon) is a mineral horizon below the A from which clay, iron, and aluminium have been removed by translocation, leaving a lighter-coloured, coarser-textured layer.

The B horizon is the subsoil — a mineral horizon that has been enriched by materials translocated from above (clay, iron oxides, organic matter) or that has undergone significant in-place weathering and structural development. It is typically denser, lighter in colour (unless iron-enriched), and less biologically active than the A horizon. The **C horizon** is the partially weathered parent material, retaining some characteristics of the original rock. The **R horizon** is the underlying unweathered bedrock. In Nigeria, deeply weathered tropical soils may not show discrete E and B horizons but instead show a gradual transition from the A through a deep red-yellow B to the C horizon at 3 to 5 metres or more depth.

Fill in the blank: The ________ horizon is the topsoil, the uppermost mineral horizon enriched with organic matter that gives it a darker colour and makes it the most biologically active and fertile layer.

Soil Horizon	**Typical Depth**	**Colour**	**Organic Matter Content**	**Biological Activity**	**Key Features**
O Horizon	Surface layer	Dark brown/black	Very high	Very active (roots, microbes, fauna)	Organic layer of decomposed plant and animal material
A Horizon	0–30 cm	Dark grey to brown	High to moderate	High (roots, earthworms, microbes)	Topsoil; zone of leaching and nutrient supply
E Horizon	30–60 cm	Light grey	Low	Moderate	Zone of eluviation; leached of clay, iron, and organic matter
B Horizon	60–120 cm	Brown, reddish, or yellow	Low	Moderate to low	Subsoil; zone of accumulation (illuviation of clay, Fe, Al oxides)
C Horizon	120–200 cm	Variable (depends on parent material)	Very low	Minimal	Weathered parent material; transition to bedrock

R Horizon	Below 200 cm	Rock colour	None	None	Unweathered bedrock; foundation material

Table 1.2: Characteristics of the major soil horizons O, A, E, B, C, and R

1.4.3 Reading a soil profile in the field

A systematic soil profile description records the characteristics of each horizon in a standardised format that allows comparison between profiles and classification of the soil. The key properties recorded for each horizon are: **horizon designation** (O, A, E, B, C, or R with qualifying suffixes), **depth** (upper and lower boundary in cm), **colour** (described using the Munsell colour chart notation of hue, value, and chroma — e.g. 10YR 4/4 for a yellowish-brown subsoil), **texture** (by the field feel test or laboratory analysis), and **structure** (the arrangement of soil particles into aggregates described by shape, size, and grade).

Additional properties recorded include: consistence (the resistance of the soil to deformation when moist, wet, and dry; described as loose, friable, firm, hard, or rigid), boundary (the distinctness and shape of the transition between horizons, described as abrupt, clear, gradual, or diffuse), mottles (irregular patches of contrasting colour indicating periodic waterlogging), roots (abundance and size class of roots present), and special features (concretions, hard pans, stone lines, bleached sand grains). In Nigeria, the most commonly observed profile features in savanna soils are deep red-yellow Bt horizons enriched with clay and iron oxides, plinthite (iron-rich material that hardens irreversibly on drying), and stone lines at depth indicating past erosion surfaces.

Fill in the blank: Soil colour in a profile description is recorded using the ________ colour chart, which describes colour by the notation of hue, value, and chroma.

Plate 1.1: A soil pit dug to expose a tropical soil profile showing distinct A, B, and C horizons with colour and texture changes

Pilot questions 1.4

1. Define the soil profile and explain why it is the fundamental unit of soil study.
2. List the major soil horizons from surface to parent material and describe the distinguishing characteristics of each.
3. What is the Munsell colour chart and why is it used to describe soil colour?
4. Describe the field procedures for recording a soil profile description.
5. Explain what mottles in a soil profile indicate about the soil's drainage history.

Series Summary

This Series has introduced the origin and formation of soils as the foundation of soil science. We began by defining soil in the pedological sense, describing its four major components (mineral matter, organic matter, water, and air) and their approximate proportions, and explaining how soil functions as a dynamic natural system in which physical, chemical, and biological processes continuously interact. We then examined the five soil-forming factors — parent material, climate, organisms, topography, and time — explaining the role and mechanisms of each in determining the properties of the soils that develop.

Following that, we covered the principal soil-forming processes: physical and chemical weathering (particularly hydrolysis, oxidation, carbonation, and hydration), the transformation, translocation, and accumulation processes that create horizon differentiation, and the humification process through which fresh organic matter is transformed into stable humus and incorporated into the A horizon. Finally, we introduced the soil profile — defining its horizons (O, A, E, B, C, and R), describing the characteristics of each, and explaining the field procedures for profile description using the Munsell colour chart and standardised morphological terminology. By completing this Series, you should now be able to achieve all nine Series Learning Outcomes (SLO 1.1 to SLO 1.9).

Glossary of Terms

- **A horizon:** the uppermost mineral soil horizon, enriched with organic matter (darker colour), biologically active, and generally the most fertile layer of the mineral soil profile; the topsoil.
- **Alluvium:** sedimentary material deposited by flowing water; forms fertile, fine-textured soils in floodplains and river valleys; a transported parent material.
- **B horizon:** the subsoil horizon enriched by materials translocated from above (clay, iron oxides, organic matter) or significantly altered by in-place weathering; typically denser and less biologically active than the A horizon.
- **C horizon:** the partially weathered parent material horizon below the B horizon, retaining some characteristics of the original geological material from which the soil formed.
- **Carbonation:** a chemical weathering process in which carbonate minerals react with carbonic acid (from CO_2 dissolved in rainwater) to produce soluble bicarbonate ions; dissolves limestone and other calcareous rocks.

- **Catena (toposequence):** the sequence of soils from ridge top to valley bottom that arises from topographic control of water redistribution, drainage, organic matter accumulation, and erosion and deposition processes.
- **E horizon:** the eluviation horizon; a mineral horizon below the A horizon from which clay, iron, and aluminium have been removed by translocation, producing a lighter-coloured, coarser-textured layer.
- **Humification:** the biological transformation of fresh organic residues into stable humus through progressive microbial decomposition and biochemical transformation of resistant compounds such as lignin.
- **Humus:** stable, dark-coloured, complex organic polymer produced from the humification of fresh organic matter; improves soil structure, water-holding capacity, cation exchange capacity, and nutrient supply.
- **Hydrolysis:** the dominant chemical weathering process for silicate minerals, in which minerals react with water to produce clay minerals and release cations (calcium, magnesium, potassium) into soil solution.
- **Illuviation:** the accumulation of materials in a lower soil horizon that have been translocated (moved downward) from an upper horizon by percolating water; the counterpart of eluviation.
- **Leaching:** the downward movement of soluble ions (calcium, magnesium, potassium, nitrate) from upper soil horizons through the soil profile and into groundwater, driven by percolating rainwater.
- **Lessivage:** the translocation of fine clay particles from the upper soil horizon to accumulate in a lower argillic B horizon; driven by percolating water carrying clay in suspension.
- **Munsell colour chart:** a standardised colour notation system used in soil profile description to specify soil colour by hue (the basic spectral colour), value (lightness), and chroma (colour saturation).
- **O horizon:** the organic surface horizon above the mineral soil, formed by the accumulation of plant litter and partially decomposed organic matter; most prominent in forested soils.

- **Oxidation:** a chemical weathering process in which iron- and manganese-containing minerals react with oxygen, producing red and yellow iron oxides (haematite, goethite) that give many Nigerian soils their characteristic colour.
- **Parent material:** the unconsolidated geological material from which soil is formed by weathering and pedogenic processes; may be in-place bedrock or transported deposits.
- **Pedogenesis:** the process of soil formation; the collective term for all the physical, chemical, and biological processes that transform parent material into soil over time.
- **Plinthite:** an iron-rich, soft to hard material found in many tropical B horizons that hardens irreversibly on repeated wetting and drying; when fully hardened forms laterite or ironstone.
- **R horizon:** the underlying unweathered bedrock below the C horizon; forms the bottom boundary of the soil profile.
- **Soil horizon:** a layer within the soil profile that is approximately parallel to the surface and differs from adjacent layers in colour, texture, structure, and chemical properties, resulting from pedogenic processes.
- **Soil profile:** the vertical cross-section of the soil from the surface to the underlying parent material, exposing all soil horizons and providing the fundamental basis for soil description and classification.
- **Toposequence (catena):** see catena; the systematic variation in soil properties across a landscape from ridge to valley that results from topographic control of pedogenic processes.
- **Weathering:** the physical disintegration and chemical decomposition of rocks and minerals at or near the Earth's surface by atmospheric agents, producing the regolith and ultimately the mineral fraction of soil.

Concept Check Questions [Series 1]

Objective Questions

1. Soil is the naturally occurring, unconsolidated ________ layer of the Earth altered by physical, chemical, and biological processes to support plant growth. (Linked to SLO 1.1)

2. The four components of a typical agricultural soil are mineral matter, organic matter, soil water, and soil ________. (Linked to SLO 1.2)
3. ________ is considered the most powerful soil-forming factor at the regional scale because it controls weathering rate and leaching intensity. (Linked to SLO 1.4)
4. The dominant chemical weathering process for silicate minerals, producing clay minerals and releasing cations, is called ________. (Linked to SLO 1.5)
5. The A horizon is the topsoil — the uppermost ________ horizon enriched with organic matter that gives it a darker colour. (Linked to SLO 1.8)

Short-Answer Questions

6. Name the five soil-forming factors and explain the role of one in determining soil properties. (Linked to SLO 1.4)
7. Distinguish between physical weathering and chemical weathering and give one example of each. (Linked to SLO 1.5)
8. Explain the processes of translocation and accumulation and describe one example of each in soil profile development. (Linked to SLO 1.6)
9. Define humification and explain the importance of humus to soil fertility. (Linked to SLO 1.7)
10. Describe the major soil horizons from surface to parent material and state one distinguishing feature of each. (Linked to SLO 1.8)

Long-Answer Questions

11. Analyse the five soil-forming factors, explaining the mechanism by which each factor influences soil development and giving examples from Nigerian farming conditions where relevant. (Linked to SLOs 1.4)
12. Discuss the soil-forming processes of weathering, transformation, translocation, and accumulation, explaining the chemical weathering reactions, how they create horizon differentiation, and the role of humification in the development of the A horizon. (Linked to SLOs 1.5, 1.6, 1.7)

13. Evaluate the soil profile as the foundation of soil science, describing the major horizons and their characteristics, explaining how a field profile description is conducted, and discussing how profile features such as colour, texture, mottles, and plinthite reflect the history of soil formation in tropical Nigeria. (Linked to SLOs 1.8, 1.9)

Answers to Concept Check Questions [Series 1]

Objective Questions

1. Surface.
2. Air.
3. Climate.
4. Hydrolysis.
5. Mineral.

Short-Answer Questions

6. The five soil-forming factors are parent material, climate, organisms, topography (relief), and time. Climate role example: temperature controls the rate of chemical weathering reactions (doubling approximately every 10°C) and rainfall determines the intensity of leaching; in Nigeria's forest zone, high rainfall and temperature combine to produce intense weathering, deep profiles, and highly leached acidic soils, while in the drier north, less intense weathering produces less leached, more fertile soils.
7. Physical weathering is the mechanical disintegration of rock into smaller fragments without change in chemical composition; example: root wedging, in which plant roots penetrate and enlarge rock cracks. Chemical weathering alters the chemical composition of minerals through reactions with water and dissolved gases; example: oxidation of iron-containing minerals producing red iron oxide (haematite) that gives Nigerian lateritic soils their characteristic red colour.
8. Translocation is the movement of materials from one part of the soil profile to another carried by percolating water; example: leaching of calcium ions from the A horizon downward through the

profile. Accumulation (illuviation) is the deposition of translocated materials in a lower horizon; example: clay particles translocated from the A horizon accumulate in the B horizon, forming an argillic horizon with higher clay content than the horizons above or below it.

9. Humification is the biological transformation of fresh organic residues into stable humus through progressive microbial decomposition; importance to soil fertility: humus supplies nutrients slowly as it mineralises; forms stable organo-mineral aggregates improving soil structure and reducing erosion; greatly increases water-holding capacity; provides cation exchange sites that retain plant-available nutrients against leaching; and gives the surface A horizon its characteristic dark colour and high biological activity.
10. O horizon: organic surface layer of accumulated plant litter and partially decomposed organic matter; most prominent in forest soils. A horizon: uppermost mineral horizon enriched with organic matter (dark colour), biologically active, most fertile mineral layer. E horizon: eluviation horizon depleted of clay, iron, and aluminium by translocation, lighter in colour and coarser in texture. B horizon: subsoil enriched by translocated materials (clay, iron oxides) or significantly weathered; typically red-yellow in Nigerian tropical soils. C horizon: partially weathered parent material retaining original rock characteristics. R horizon: unweathered bedrock.

Long-Answer Questions

11. Basic response: Parent material: mineral composition determines fertility and pH (basic rocks produce fertile neutral soils; granite produces sandy, acidic, nutrient-poor soils). Climate: most powerful regional factor; high temperature and rainfall (Nigerian forest zone) accelerate weathering, leaching, and deep profile development; low rainfall (Nigerian north) produces less weathered, more fertile soils. Organisms: plants add organic matter; microorganisms cycle nutrients; earthworms and termites mix horizons and improve structure; termite mounds redistribute soil across large areas. Topography: ridges are shallow and well-drained; valleys accumulate water, organic matter, and soluble materials; catena (toposequence) describes the resulting spatial pattern. Time: young soils resemble parent material; old soils (Nigerian basement complex) are deeply weathered, clay-dominated, and nutrient-poor.
12. Value-added response: The interaction between the five factors is more important than any single factor in explaining Nigerian soil diversity. The combination of old, highly weathered basement complex parent material + high rainfall and temperature + flat to gently undulating topography has produced the deep, red, kaolinitic, nutrient-poor Ultisols and Oxisols that dominate the forest

and derived savanna zones and require careful management to sustain agricultural productivity. The same parent material under semi-arid northern conditions produces Alfisols with greater inherent fertility and less severe weathering — demonstrating that climate is the decisive variable in this combination.

13. Basic response: Physical weathering: thermal expansion, root wedging, abrasion — disintegrate rock without chemical change. Chemical weathering: hydrolysis (primary process for silicates, produces clay minerals and releases cations), oxidation (iron and manganese to oxides — red and yellow colours), carbonation (limestone dissolution), hydration (mineral swelling). Transformation: primary minerals to secondary clay minerals and oxides in place. Translocation: leaching of soluble ions downward; lessivage of clay particles to B horizon. Accumulation: clay in argillic B; iron oxides in lateritic B; humus formation: fresh litter -> microbial decomposition of sugars and proteins -> transformation of lignin -> humic substances -> organo-mineral aggregates -> dark A horizon.
14. Value-added response: The chemical weathering process that most profoundly shapes the agricultural potential of Nigerian soils is hydrolysis of the primary silicate minerals (feldspars, micas) in the basement complex rocks. This process releases the base cations (Ca, Mg, K) that were originally locked in the mineral lattice and makes them available to plants — but in a highly leached system these bases are quickly lost to leaching, leaving behind the secondary clay minerals (predominantly kaolinite in Nigeria) and iron oxides that characterise highly weathered tropical soils. Understanding this geochemical cascade from fresh feldspar to kaolinite clay to leached, acidic, low-CEC soil explains why Nigerian basement complex soils are inherently less fertile than many soils of similar age in drier climates where leaching is less intense.
15. Basic response: Horizons: O (organic surface), A (dark, organic-rich topsoil, biologically active), E (eluviated, light-coloured, clay-depleted), B (clay and iron-enriched subsoil), C (partly weathered parent material), R (bedrock). Field description: horizon designation, depth, Munsell colour, texture (field feel test), structure (shape, size, grade of aggregates), consistence, boundary character, mottles, roots, special features. Nigerian profile features: deep red-yellow B horizons with iron oxide and clay enrichment; plinthite (soft to hard iron-rich material) in many lower B horizons that hardens irreversibly; stone lines at depth indicating ancient erosion surfaces; mottles in seasonally waterlogged valley soils.
16. Value-added response: Plinthite is one of the most agronomically significant profile features in Nigerian soils and one of the most frequently misunderstood. It exists as soft, iron-rich, mottled material in the subsoil of many Nigerian B horizons and causes few problems while it remains moist and buried; but when exposed at the surface through erosion and subjected to repeated

drying, it irreversibly hardens into ironstone (laterite), forming an impenetrable layer that prevents root development and equipment penetration. Recognising plinthite in a soil profile — by its characteristic soft, mottled, red-and-white iron-rich appearance in the lower B or BC horizon — and understanding that deep tillage, heavy grazing, or intensive land clearance can expose it, is therefore one of the most practically important skills a student can acquire from this course.

Answers to Pilot Questions [Series 1]

Part 1.1: The Nature and Importance of Soil

1. Soil in the pedological sense is the naturally occurring, unconsolidated surface layer of the Earth that has been altered by physical, chemical, and biological processes to support plant growth; it differs from unweathered parent material in having a distinct composition (mineral plus organic), a pore structure created by biological activity, a living community of microorganisms and other organisms, and chemical properties (pH, nutrient availability, cation exchange capacity) that reflect its history of pedogenic transformation rather than the simple mineral composition of the parent rock.
2. Any four: food production (soil supports 95 per cent of global food supply; its degradation directly threatens food security); water filtration and storage (soil filters and purifies water percolating to aquifers, removing pollutants, pathogens, and excess nutrients); nutrient cycling (soil cycles carbon, nitrogen, phosphorus, and other elements between the biosphere and atmosphere, regulating atmospheric chemistry); biodiversity support (one quarter of all living species live in soil; their loss diminishes ecosystem function); carbon storage (soil organic matter sequesters atmospheric carbon, playing a major role in climate regulation).
3. Mineral matter (approximately 45 per cent by volume): weathered rock and mineral particles that provide structural framework and reservoir of most nutrient elements. Organic matter (approximately 5 per cent): living organisms, fresh residues, and humus that profoundly influence fertility, structure, and water retention. Soil water (approximately 25 per cent): fills pore spaces, transports nutrients to roots, mediates chemical reactions. Soil air (approximately 25 per cent): also fills pore spaces, provides oxygen for root and microbial respiration; inversely related to water content.

4. Soil water and soil air are inversely related because they both occupy the same pore spaces in the soil; when a soil becomes waterlogged after rainfall, water fills the pores and displaces air; as the soil drains, water moves downward under gravity and air re-enters from above to replace it; there is a fixed total pore volume in a soil and the fractions occupied by water and air always sum to that total, so an increase in one necessarily decreases the other.
5. Soil is described as a dynamic natural system because it is not a static, inert material but a continuously changing body in which multiple processes interact: physical processes (wetting, drying, freezing, tillage) alter structure; chemical processes (mineral dissolution, ion exchange, pH changes, oxidation-reduction) alter nutrient availability and mineral composition; biological processes (organic matter decomposition, root growth, microbial activity) cycle nutrients and create pore structure; and all these processes respond to and interact with management practices and environmental conditions, meaning soil properties can change significantly within seasons or years.

Part 1.2: Soil-Forming Factors

1. Parent material is the unconsolidated geological material from which soil is formed by weathering and pedogenic processes; two examples of transported parent materials in Nigeria: alluvium (water-deposited sediments in Niger Delta floodplains and river valleys, forming fertile, fine-textured soils); aeolian deposits (wind-blown sand and silt in the semi-arid north, forming lighter-textured, less fertile soils in the Sudan and Sahel zones).
2. Basic igneous rocks (basalt, dolerite) are rich in calcium, magnesium, and iron-bearing silicate minerals; on weathering they release these base cations into the soil solution, producing fertile soils with neutral to slightly acid pH. Acid igneous rocks (granite) are dominated by quartz and feldspar with lower calcium and magnesium content; they weather to produce sandy, coarser-textured, nutrient-poorer soils with more acidic pH. Siliceous sedimentary rocks (sandstone) produce sandy, highly permeable, low-fertility soils; calcareous rocks (limestone) produce clay-rich, well-buffered, fertile soils near neutral pH.
3. Climate is the most powerful regional soil-forming factor because: temperature controls the rate of all chemical weathering reactions (roughly doubling every 10°C), so hot climates produce more intensely weathered soils; rainfall controls the amount of water available for weathering reactions and the intensity of leaching, so high-rainfall climates produce deeply leached, base-poor, acidic soils, while low-rainfall climates retain more soluble nutrients; over continental and regional scales, the pattern of soil types mirrors the pattern of climate zones more closely than any other factor.

4. Any two: plants — add organic matter to the soil surface through leaf litter fall and to the soil interior through root turnover and root exudates; root channels create macropores that improve water infiltration and air movement in the soil profile. Microorganisms — decompose organic residues, releasing nutrients from organic compounds; drive nitrogen fixation (legume-Rhizobium symbiosis and free-living fixers) that adds new nitrogen to the soil system; mediate most nutrient cycling reactions in the soil.
5. A catena (toposequence) is the sequence of different soils that occurs along a hillslope from ridge top to valley bottom, arising from the influence of topography on water redistribution, erosion, and deposition processes; on ridge tops, water drains rapidly and soils are well-drained, shallow, and nutrient-poor; on mid-slopes, moderate drainage produces intermediate soils; in valley bottoms, water from upslope areas accumulates, soils are wetter, deeper, and richer in accumulated organic matter and soluble minerals, and may be periodically waterlogged, producing mottled, gleyed profiles with poor drainage characteristics.

Part 1.3: Soil-Forming Processes

1. Physical weathering disintegrates rock into smaller fragments without changing chemical composition; two examples: thermal expansion and contraction (heating and cooling cycles create repeated stress that fractures rock surfaces); root wedging (plant roots penetrate rock cracks and mechanically enlarge them as roots grow). Chemical weathering alters the chemical composition of minerals by reactions with water and gases; two examples: hydrolysis of feldspar (releases potassium and produces clay minerals); oxidation of iron-bearing minerals (produces red haematite or yellow goethite iron oxides).
2. Hydrolysis is the reaction of silicate minerals with water (often slightly acidic from dissolved CO_2), in which hydrogen ions from the water replace cations (calcium, potassium, magnesium) in the mineral structure; this breaks down the crystal lattice of the primary mineral (feldspar, mica), releasing soluble cations into soil solution and producing secondary clay minerals (kaolinite, smectite, illite) as residual products; it is the most important chemical weathering process for silicates because silicates make up more than 90 per cent of the Earth's crust and hydrolysis is the fundamental reaction that converts them into the clay fraction that dominates the fine mineral component of most soils.
3. Translocation is the movement of materials from one part of the soil profile to another, carried by percolating water in solution or suspension; example: clay particles (lessivage) are carried from the A horizon downward to accumulate in the B horizon. Accumulation (illuviation) is the deposition or concentration of those translocated materials in the receiving horizon; example: the

clay particles translocated from the A horizon accumulate in the B horizon to form an argillic horizon with higher clay content than horizons above or below it — the same clay particles are involved in both translocation (their downward movement) and accumulation (their deposition in the B).

4. Humification is the biological transformation of fresh organic residues (plant litter, roots, animal matter) into stable humus through progressive microbial activity; stages: (1) colonisation of fresh litter by bacteria and fungi; (2) rapid decomposition of easily degradable compounds (sugars, starch, proteins); (3) slower decomposition of structural compounds (cellulose); (4) very slow transformation of the most resistant compounds (lignin, waxes) through complex biochemical reactions; (5) formation of large, dark, complex humic polymers (humic acid, fulvic acid, humin) that are resistant to further rapid decomposition.
5. Humus improves soil fertility by: supplying nutrients slowly as it mineralises through continued microbial activity (nitrogen, phosphorus, sulphur released as plant-available ions); improving soil structure through formation of stable organo-mineral aggregates that resist erosion and improve pore structure; greatly increasing water-holding capacity because humus can absorb several times its own weight in water; providing cation exchange sites (high charge density per unit mass, particularly fulvic and humic acids) that retain plant nutrients against leaching; and giving the A horizon its dark colour, which promotes warming and greater biological activity.

Part 1.4: The Soil Profile

1. The soil profile is the vertical cross-section of the soil from the surface to the underlying parent material, exposing all soil horizons as distinct horizontal layers; it is the fundamental unit of soil study because it reveals the entire history of the soil in one vertical exposure — showing what parent material was present, what processes have acted on it, how deeply those processes have penetrated, and what chemical and physical conditions prevail at each depth; all soil classification systems are based on profile characteristics, and all management recommendations for drainage, irrigation, fertility, and tillage depend on understanding the profile of the soil being managed.
2. O horizon (organic surface layer, forest soils): accumulated plant litter and decomposing organic matter above the mineral soil. A horizon (topsoil): uppermost mineral horizon, dark colour from organic matter enrichment, biologically active, most fertile mineral layer. E horizon (eluviation): lighter-coloured layer depleted of clay, iron, and aluminium by translocation, coarser texture. B horizon (subsoil): enriched by translocated clay and iron oxides (typically red-yellow in Nigerian soils), denser, less biologically active. C horizon: partly weathered parent material, retaining some original rock characteristics. R horizon: unweathered bedrock.

3. The Munsell colour chart is a standardised colour notation system used to describe soil colour objectively and reproducibly by specifying three dimensions: hue (the basic spectral colour, e.g. 10YR = yellowish-brown range), value (the lightness of the colour from 0 = black to 10 = white), and chroma (the colour saturation or intensity from 0 = grey to 8+ = vivid); it is used because soil colour varies enormously in the field, people perceive and describe colour differently without a standard reference, and colour is a critical indicator of organic matter content (dark A horizons), iron oxide type and content (red to yellow B horizons), and drainage conditions (grey or mottled colours indicating waterlogging).
4. Field profile description procedure: (1) dig a soil pit to at least 1.5 m depth or until bedrock or impenetrable hardpan is reached, with one face vertical and in full light; (2) identify horizon boundaries by systematic examination of the freshly exposed face from top to bottom; (3) for each horizon, record: horizon designation, upper and lower depth, colour by Munsell chart (moist and dry if possible), texture by field feel test, structure (type, class, grade), consistence (dry, moist, wet), boundary character, mottles (colour, abundance, size), roots (abundance, size), and any special features (concretions, hard pans, plinthite, stone lines); (4) photograph the profile with a scale bar; (5) collect representative soil samples from each horizon for laboratory analysis.
5. Mottles in a soil profile are irregular patches of colour contrasting with the matrix (background) colour of the horizon; they indicate that the soil is or has been subjected to periodic waterlogging and anaerobic conditions; when a soil is waterlogged, the oxygen in the pore water is consumed by microbial respiration and conditions become anaerobic; iron is chemically reduced (from $Fe3+$ to $Fe2+$, which is soluble and grey in colour) and moves away from waterlogged zones; when the soil dries, iron is re-oxidised and precipitates as orange-red iron oxide mottles in the zones that remain aerated; the pattern and abundance of mottles therefore reveals the frequency, duration, and depth of waterlogging, which is critical information for drainage design and crop selection.

References and Attributions [Series 1]

Textual References (Books and External Sources)

- Brady, N. C., & Weil, R. R. (2016). The nature and properties of soils (15th ed.). Pearson Education.
- Eswaran, H., Rice, T., Ahrens, R., & Stewart, B. A. (2003). Soil classification: A global desk reference. CRC Press.
- Juo, A. S. R., & Franzluebbers, K. (2003). Tropical soils: Properties and management for sustainable agriculture. Oxford University Press.
- Soil Survey Staff. (1999). Soil taxonomy: A basic system of soil classification for making and interpreting soil surveys (2nd ed.). USDA Natural Resources Conservation Service.
- FAO (Food and Agriculture Organization of the United Nations). (2006). World reference base for soil resources. FAO.
- FAO (Food and Agriculture Organization of the United Nations). (2025). Guidelines for sustainable agriculture. FAO.

Figures, Plates, Tables, and Boxes

- Figure 1.1: Importance of soil mind map Attribution: AI generated using prompt "Generate a mind map showing soil at the centre with roles in food production, water filtration, carbon storage, nutrient cycling, biodiversity, and infrastructure." Suggested OER search string: "importance of soil roles food production water filtration nutrient cycling OER diagram".
- Figure 1.2: Soil components pie chart Attribution: AI generated using prompt "Generate a pie chart showing the four components of a typical agricultural soil: mineral matter 45%, organic matter 5%, soil water 25%, and soil air 25%." Suggested OER search string: "soil components mineral organic matter water air percentages pie chart OER".
- Figure 1.3: Soil system interactions diagram Attribution: AI generated using prompt "Generate a triangle or Venn diagram showing the three interacting domains of the soil system: physical, chemical, and biological, with arrows showing their mutual interactions." Suggested OER search string: "soil system interactions physical chemical biological components OER diagram".
- Table 1.1: Parent materials and soil properties table Attribution: AI generated using prompt "Generate a table listing common parent materials including basalt, granite, sandstone, alluvium, and shale with their mineralogy, weathering products, and typical soil properties." Suggested

OER search string: "parent material soil formation mineral composition soil properties table OER".

- Figure 1.4: Climate influence on Nigerian soil formation Attribution: AI generated using prompt "Generate a diagram showing how increasing rainfall and temperature from north to south across Nigeria influences soil weathering depth, leaching, and soil type." Suggested OER search string: "climate influence soil formation Nigeria rainfall temperature leaching OER diagram".
- Figure 1.5: Catena cross-section diagram Attribution: AI generated using prompt "Generate a cross-section diagram of a catena showing soil depth, drainage, and horizon changes from ridge top through mid-slope to valley bottom." Suggested OER search string: "catena toposequence soil profile changes ridge valley bottom OER diagram".
- Figure 1.6: Weathering processes diagram Attribution: AI generated using prompt "Generate a two-column diagram showing physical weathering processes and chemical weathering processes with the products of each." Suggested OER search string: "physical chemical weathering processes products hydrolysis oxidation carbonation OER".
- Figure 1.7: Transformation, translocation, and accumulation diagram Attribution: AI generated using prompt "Generate a cross-section diagram of a soil profile showing transformation, translocation with arrows, and accumulation zones." Suggested OER search string: "soil profile transformation translocation accumulation illuviation OER diagram".
- Figure 1.8: Humification stages flowchart Attribution: AI generated using prompt "Generate a flowchart showing the stages of humification from fresh plant litter through microbial decomposition and transformation to stable humus and A horizon formation." Suggested OER search string: "humification stages fresh litter humus formation A horizon soil OER diagram".
- Figure 1.9: Soil profile horizons diagram Attribution: AI generated using prompt "Generate a labelled cross-section diagram of a generalised soil profile showing O, A, E, B, C, and R horizons with approximate depths, colours, and descriptions." Suggested OER search string: "soil profile horizons O A E B C R labelled diagram cross-section OER".
- Table 1.2: Soil horizons characteristics table Attribution: AI generated using prompt "Generate a table listing the major soil horizons O, A, E, B, C, and R with their depth, colour, organic matter content, biological activity, and key features." Suggested OER search string: "soil horizons characteristics A B C E O R table OER".
- Plate 1.1: Tropical soil pit with visible horizons Attribution: AI generated using prompt "Generate an image of an open soil pit in a tropical environment showing a clear soil profile with dark A horizon, red-yellow B horizon, and lighter C horizon with a scale bar." Suggested OER search string: "tropical soil pit profile A B C horizon red yellow OER image".

Course code: AGE 202

Course title: Introduction to Soil Science

Course credit load: 2 Units

Series 2: Physical Properties and Classification of Soils

- **Part 2.1: Soil Texture**
  - Sub Part 2.1.1: Soil separates: sand, silt, and clay
  - Sub Part 2.1.2: Soil textural classes and the textural triangle
  - Sub Part 2.1.3: Importance of texture to soil behaviour and management
- **Part 2.2: Soil Structure, Consistence, and Colour**
  - Sub Part 2.2.1: Soil structure: types, grades, and sizes
  - Sub Part 2.2.2: Soil consistence and soil colour
  - Sub Part 2.2.3: Influence of structure on soil behaviour
- **Part 2.3: Soil Classification Systems**
  - Sub Part 2.3.1: Principles and purpose of soil classification
  - Sub Part 2.3.2: USDA Soil Taxonomy
  - Sub Part 2.3.3: FAO World Reference Base and Nigerian soil classification
- **Part 2.4: Soil Survey**
  - Sub Part 2.4.1: Purpose and types of soil survey
  - Sub Part 2.4.2: Soil survey methods and mapping units
  - Sub Part 2.4.3: Using soil survey information for agricultural planning

Introduction

The physical properties of soil — its texture, structure, consistence, and colour — are the most directly observable characteristics of soil and the ones that most immediately determine how a soil behaves under cultivation, irrigation, drainage, and erosion. A clay soil and a sandy soil respond entirely differently to the same rainfall event, the same tillage implement, and the same fertiliser application, yet both may produce good crops if managed appropriately for their physical properties. Developing the ability to read and interpret soil physical properties is therefore one of the most practically valuable skills an agriculture student can acquire.

The aim of this Series is to introduce you to the key physical properties of soil, particularly texture and structure, and to connect these properties to soil classification systems and soil survey as the tools through which soil knowledge is organised and communicated for agricultural planning.

We shall commence this Series by examining soil texture and the textural triangle. Next, we will study soil structure, consistence, and colour. Following that, we will cover the major soil classification systems including USDA Soil Taxonomy and the FAO World Reference Base. Finally, we will wrap up with soil survey — its purpose, methods, and use in agricultural planning.

Series Learning Outcomes

Upon completing this Series, you should be able to:

- **SLO 2.1** define the soil separates, describe their properties, and determine soil texture by the field feel method (Linked to Part 2.1),
- **SLO 2.2** use the textural triangle to determine the textural class of a soil given its particle size composition (Linked to Part 2.1),
- **SLO 2.3** explain how soil texture influences water-holding capacity, drainage, aeration, and tillage behaviour (Linked to Part 2.1),

- **SLO 2.4** describe the types, grades, and sizes of soil structure and explain how structure develops (Linked to Part 2.2),
- **SLO 2.5** describe soil consistence and soil colour and explain their diagnostic significance (Linked to Part 2.2),
- **SLO 2.6** explain the principles of soil classification and describe the major orders of USDA Soil Taxonomy (Linked to Part 2.3),
- **SLO 2.7** describe the FAO World Reference Base and explain how major Nigerian soil types are classified (Linked to Part 2.3),
- **SLO 2.8** explain the purpose and types of soil survey (Linked to Part 2.4), and
- **SLO 2.9** describe soil survey methods and mapping units and explain how survey data are used for agricultural planning (Linked to Part 2.4).

2.1 Soil Texture

2.1.1 Soil separates: sand, silt, and clay

Soil texture refers to the relative proportions of the three mineral particle size classes — sand, silt, and clay — in a soil. These size classes are called **soil separates**. In the USDA classification system (the most widely used internationally): **sand** particles range from 0.05 to 2.0 mm diameter, are visible to the naked eye, feel gritty, and have a large surface area per unit mass. **Silt** particles range from 0.002 to 0.05 mm, are not individually visible to the naked eye, feel silky or floury when wet. **Clay** particles are smaller than 0.002 mm (2 micrometres), are colloidal in size, feel sticky and plastic when wet, and have an enormous surface area relative to their mass.

The distinction between these separates is not merely one of size but of mineralogy and surface chemistry. Sand and silt particles consist predominantly of primary minerals (quartz, feldspars) that are chemically relatively inert. Clay particles consist of secondary clay minerals (kaolinite, smectite, illite, montmorillonite) that are crystalline aluminosilicate compounds with a net negative surface charge, allowing them to attract and hold positively charged nutrient cations. This cation exchange capacity of clay is one of the most important chemical properties of the mineral soil fraction. Soils with more clay have higher nutrient-holding capacity but also poorer drainage, higher shrink-swell potential, and greater resistance to tillage.

Fill in the blank: Clay particles are smaller than ________ mm in diameter, are colloidal in size, and carry a net negative surface charge that allows them to attract and hold plant nutrient cations.

Soil Separate	Diameter Range	Visual Detectability	Field Feel	Dominant Minerals	Key Properties
Sand	2.0 – 0.05 mm	Easily visible grains	Gritty, coarse texture	Mostly quartz, some feldspar	High drainage, low water-holding, low fertility
Silt	0.05 – 0.002 mm	Barely visible under naked eye	Smooth, floury feel when dry	Quartz, feldspar, mica	Moderate water-holding, medium fertility, prone to erosion
Clay	< 0.002 mm	Not visible without microscope	Sticky when wet, hard when dry	Aluminosilicates (kaolinite, montmorillonite, illite)	High water-holding, poor drainage, high nutrient retention

Table 2.1: USDA soil separate size classes with diameter ranges, visual appearance, feel, and mineral composition

2.1.2 Soil textural classes and the textural triangle

The textural triangle is the standard diagram used to determine the textural class of a soil from its percentage sand, silt, and clay contents. The triangle has three sides corresponding to the three separates; a point within the triangle represents a soil with a specific combination of sand, silt, and clay percentages, and falls within a named textural class zone. The twelve USDA textural classes are: sand, loamy sand, sandy loam, loam, silt loam, silt, sandy clay loam, clay loam, silty clay loam, sandy clay, silty clay, and clay.

Loam is the textural class with approximately equal contributions from sand, silt, and clay fractions (approximately 23 per cent clay, 28 per cent silt, and 52 per cent sand), and is considered the most productive textural class for most crops because it combines good water-holding capacity, adequate drainage, and relatively easy tillage. The field feel test allows a trained observer to estimate textural class without laboratory analysis: sandy soils feel gritty and will not form a ribbon; clay soils form a long, smooth ribbon when squeezed between thumb and forefinger; loam and intermediate classes form short ribbons of varying length and smoothness. Laboratory determination of texture is done by the hydrometer method (measuring sedimentation rates of the different size classes in water).

Fill in the blank: The ________ triangle is the standard diagram used to determine soil textural class from the percentages of sand, silt, and clay in the soil sample.

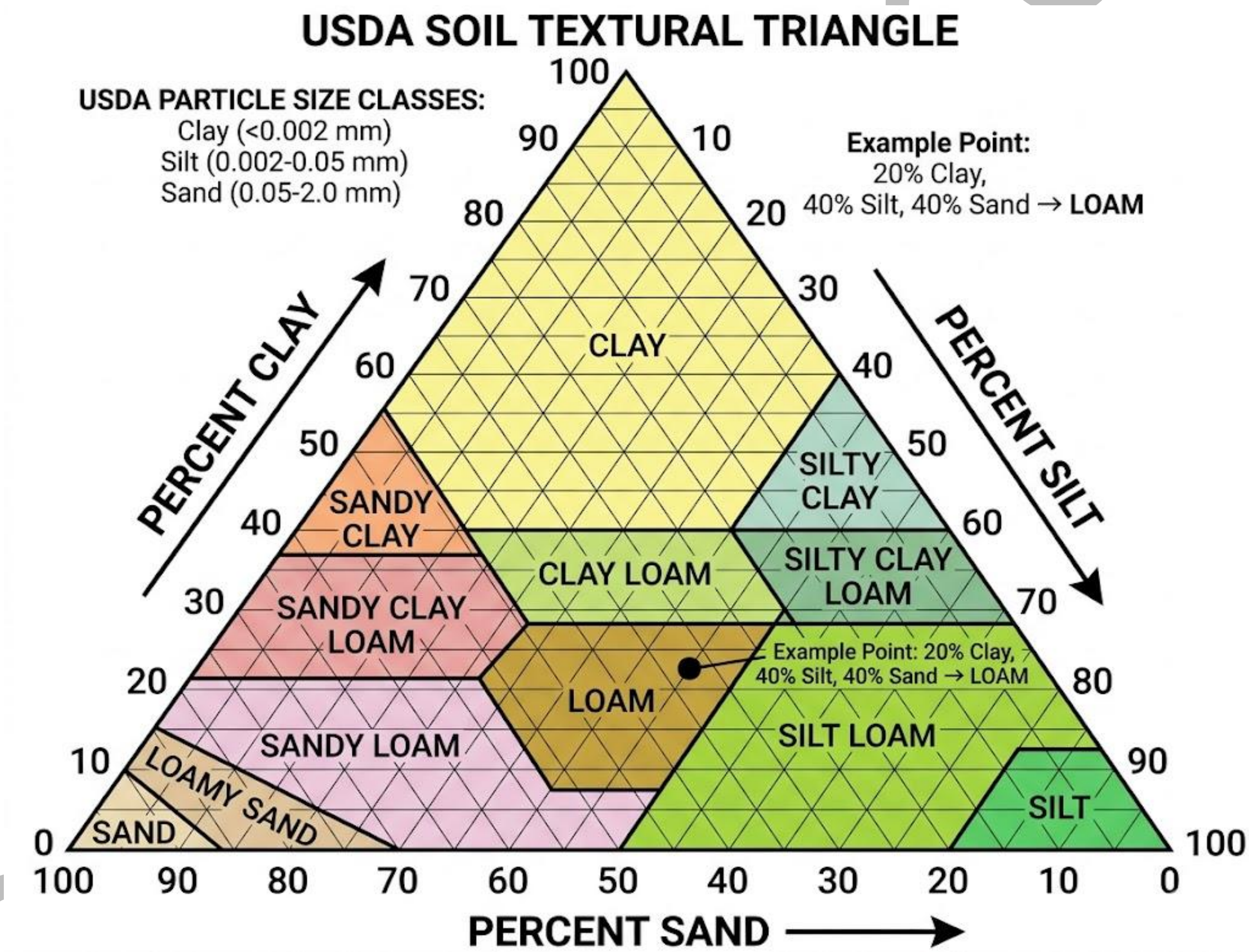

Figure 2.1: USDA soil textural triangle showing the twelve textural classes with percentage sand, silt, and clay axes

2.1.3 Importance of texture to soil behaviour and management

Soil texture is the single most important physical property because it influences virtually all other soil physical, chemical, and biological properties. **Water-holding capacity** increases with clay content: clay soils hold more total water but also hold more water so tightly that plants cannot extract it (the non-available fraction); sandy soils hold less total water but a higher proportion is plant-available. **Drainage and aeration**: sandy soils drain rapidly and are well aerated; clay soils drain slowly and may become waterlogged, restricting root aeration.

Nutrient-holding capacity (cation exchange capacity, CEC) increases with clay content because clay particles carry the negative surface charges that bind nutrient cations; sandy soils have very low CEC and nutrients leach rapidly. Tillage behaviour: clay soils are difficult to work — they are very hard when dry, sticky and plastic when wet, and have a narrow workable moisture range; sandy soils are easy to till but compact less well. Erosion susceptibility: silty soils are the most erodible because silt particles are easily detached but do not aggregate strongly; clay soils are less erodible because they form stable aggregates. In Nigeria, the highly weathered kaolinitic clays dominant in the south have lower plasticity and CEC than smectitic clays but are still significantly more water-retentive than the sandy soils of the north.

Fill in the blank: Nutrient-holding capacity (cation exchange capacity) increases with ________ content because clay particles carry negative surface charges that bind positively charged nutrient cations.

Soil Type	Water-Holding Capacity	Drainage	Aeration	CEC (Cation Exchange Capacity)	Tillage Difficulty	Erosion Susceptibility
Sandy soil	Very low	Excellent (rapid)	High	Low	Easy to till	High (wind erosion common)
Loam soil	Moderate to high	Good balance	Good balance	Moderate	Moderate (ideal for farming)	Moderate

Clay soil	Very high	Poor (slow)	Low	High	Difficult (sticky when wet, hard when dry)	Low (resists erosion but prone to compaction)

Table 2.2: Comparison of sandy, loamy, and clay soils across key physical and chemical properties

Pilot questions 2.1

1. State the diameter range of sand, silt, and clay particles according to the USDA classification.
2. Explain why clay particles have much higher nutrient-holding capacity than sand particles.
3. Describe how the textural triangle is used to determine the textural class of a soil.
4. Explain the field feel test for estimating soil texture and describe the characteristics of a sandy soil and a clay soil.
5. Explain why loam is considered the most productive textural class for most crops.

2.2 Soil Structure, Consistence, and Colour

2.2.1 Soil structure: types, grades, and sizes

Soil structure is the arrangement of individual soil particles (sand, silt, clay, and organic matter) into larger aggregates called peds or clods, separated by pores and planes of weakness. The type, grade, and size of the structural units are the three parameters used to describe soil structure in a profile description. **Structure types** describe the shape of the aggregates: granular and crumb structures (rounded, porous aggregates common in well-managed A horizons); blocky structures (angular or subangular blocks common in B horizons); prismatic and columnar structures (vertical columns common in subsoils with high shrink-swell activity); platy structures (horizontal plates caused by compaction or depositional layering).

Structure grade describes the development of the aggregates: structureless means either single-grain (individual particles with no aggregation, as in sands) or massive (one coherent block with no aggregation); weak grade means poorly formed, indistinct aggregates; moderate grade means well-formed, distinct aggregates that break cleanly along pores and planes of weakness; strong grade means very well-formed, durable aggregates that resist breakdown. Structure size refers to the diameter of individual aggregates, classified as very fine, fine, medium, coarse, and very coarse, with the ranges varying by structure type. Well-developed granular structure in the A horizon is the hallmark of a biologically active, well-managed soil.

Fill in the blank: Soil structure ________ describes the development of aggregates from structureless through weak and moderate to strong, reflecting the durability and distinctness of the peds.

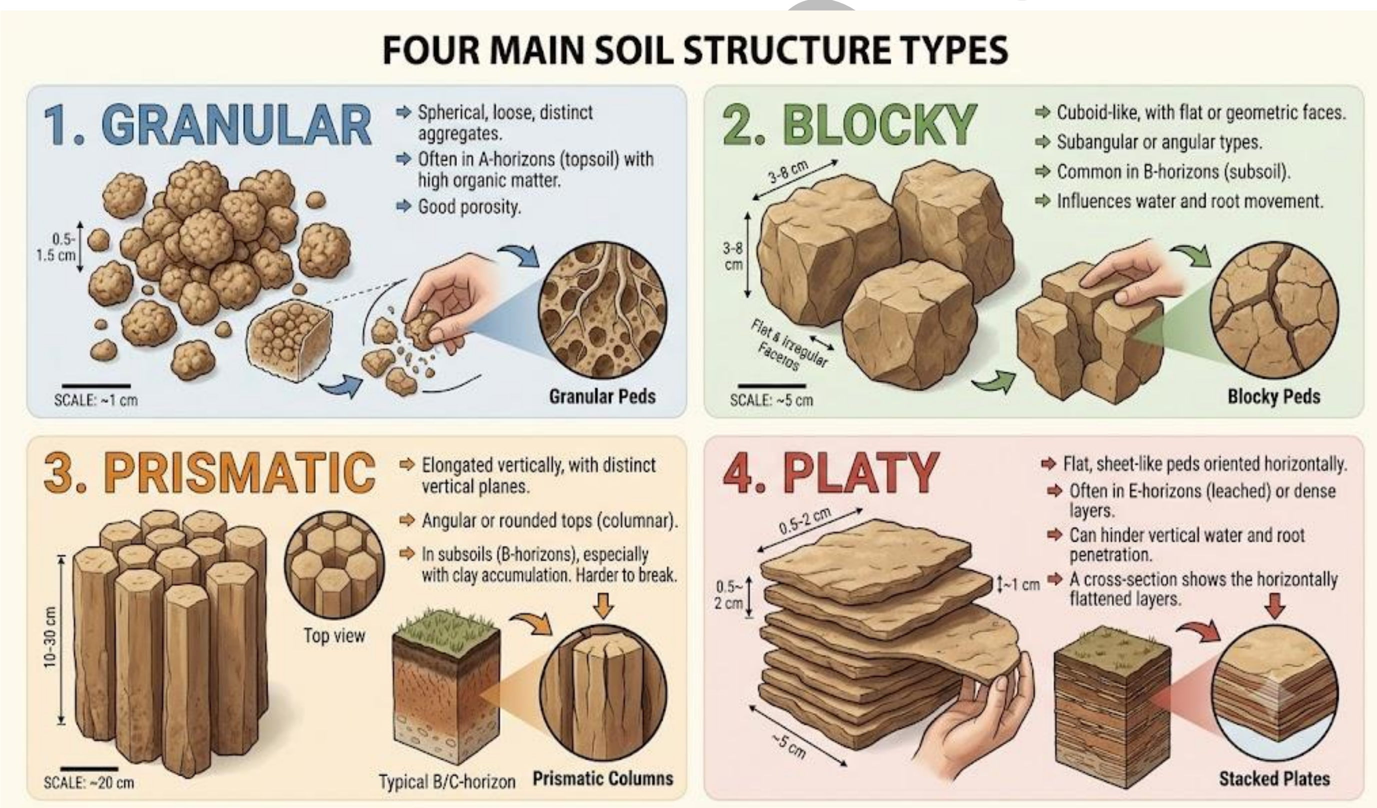

Figure 2.2: Diagram showing the main types of soil structure with drawings of granular, blocky, prismatic, and platy aggregate shapes

2.2.2 Soil consistence and soil colour

Soil consistence describes the resistance of a soil to deformation and rupture at different moisture states. **Dry consistence** ranges from loose (non-coherent) through soft, slightly hard, hard, very hard, to extremely hard. **Moist consistence** is described as loose, very friable, friable (crumbles easily with moderate force — the ideal condition for seedbed preparation), firm, very firm, and extremely firm. **Wet consistence** is described by two properties: stickiness (non-sticky, slightly sticky, sticky, very sticky) and plasticity (non-plastic, slightly plastic, plastic, very plastic). Consistence is an important practical property for timing tillage operations.

Soil colour is one of the most informative visual properties of a soil horizon and is described using the Munsell colour notation (hue, value, chroma) introduced in Series 1. The colour of a soil horizon reflects its composition and history: dark (low value) colours in the A horizon indicate high organic matter content; red and yellow colours (high chroma, 5YR to 10YR hues) in the B horizon indicate iron oxide accumulation from oxidising conditions; grey, blue-grey, and olive colours (low chroma, gleyed) indicate reducing conditions from waterlogging and anaerobic decomposition of organic matter; white and pale colours in the C horizon indicate calcareous or siliceous parent material. Colour is the most rapidly assessed soil property in the field and provides a quick first indication of the processes dominant in each horizon.

Fill in the blank: Grey, blue-grey, and olive colours with low chroma (________ colours) in a soil horizon indicate reducing conditions caused by prolonged waterlogging and anaerobic decomposition.

Soil Colour Group	Munsell Notation Range	Organic Matter Content	Iron Oxide Type	Drainage Conditions	Pedogenic Significance
Dark/Black soils	10YR 2/1 – 10YR 3/2	Very high	Minimal iron influence	Good moisture retention	Indicates high organic matter, common in O and A horizons
Brown soils	10YR 4/3 – 10YR 5/4	Moderate	Hematite and goethite	Well-drained	Typical of fertile loam soils with

					balanced organic matter
Red soils	2.5YR 4/6 – 5YR 5/8	Low	Hematite dominant	Well-drained, oxidizing	Strongly weathered, iron-rich soils; common in tropics
Yellow soils	10YR 6/6 – 10YR 7/8	Low	Goethite dominant	Moderately drained	Indicates humid conditions with slower oxidation
Grey soils	10YR 5/1 – 10YR 6/2	Low	Reduced iron (Fe^{2+})	Poorly drained, waterlogged	Gleyed soils; anaerobic conditions, common in wetlands
White soils	10YR 8/1 – 10YR 8/2	Very low	Minimal iron; silica, carbonates	Excessively drained	Leached, nutrient-poor soils; often sandy or calcareous

Table 2.3: Soil colour interpretation — common Munsell colour ranges and their pedogenic significance

2.2.3 Influence of structure on soil behaviour

Soil structure profoundly modifies the behaviour of a given texture. A clay soil with well-developed granular or subangular blocky structure has abundant macropores between aggregates that allow rapid drainage and good aeration despite the clay texture; the same clay without structure (massive) is almost impermeable. Structure influences: **infiltration and drainage** (macropores between aggregates conduct water rapidly; massive or platy structure restricts infiltration); **aeration** (macropores supply oxygen for root and microbial respiration); **root penetration** (roots follow pores between aggregates; massive or extremely hard structures prevent root extension).

Structure also influences soil erodibility and tillage draught. Well-structured soils with stable aggregates resist raindrop impact and surface sealing, reducing surface runoff and erosion; poorly structured or structureless soils form surface crusts easily that impede germination and increase erosion. Management practices that improve and maintain soil structure include:

additions of organic matter (which acts as a cement binding mineral particles into aggregates), reduced tillage (which avoids breaking down aggregates), cover cropping (which protects against raindrop impact and adds organic matter), and avoiding traffic on wet soils (which causes compaction and destroys macropores). In Nigeria, continuous cropping without organic matter additions progressively destroys soil structure, leading to surface crusting, reduced infiltration, and increased erosion.

Fill in the blank: Well-developed soil structure creates ________ between aggregates that allow rapid water drainage and good aeration even in clay soils that would otherwise be poorly drained.

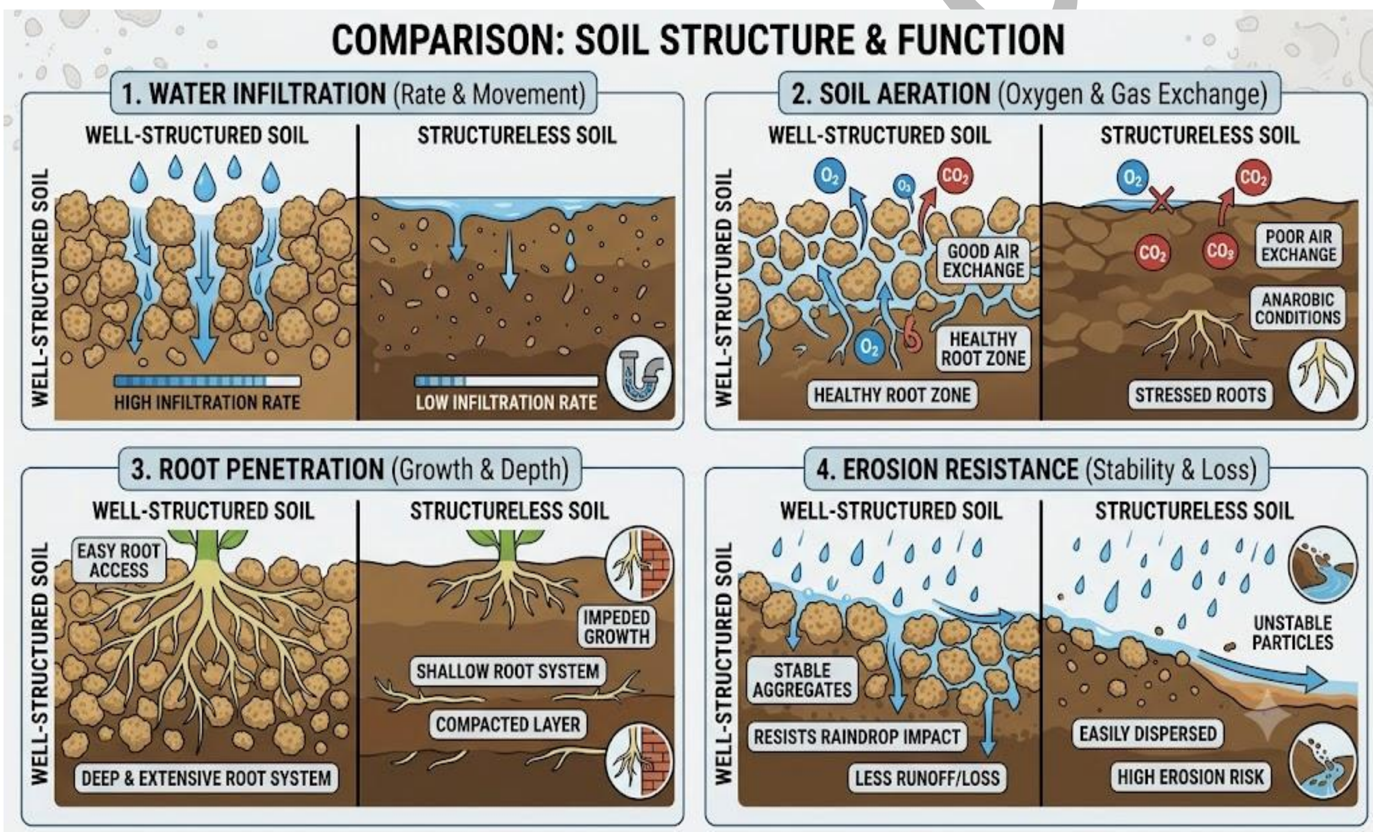

Figure 2.3: Diagram showing how soil structure influences infiltration, aeration, root penetration, and erosion resistance

Pilot questions 2.2

1. Name the four main types of soil structure and state where each is typically found in the soil profile.

2. Explain what soil structure grade means and describe the difference between weak and strong grade structures.
3. Describe what is meant by friable moist consistence and explain why it is considered the ideal condition for tillage.
4. Explain what gleyed (low-chroma grey) colours in a soil horizon indicate about the soil's drainage history.
5. Explain how additions of organic matter improve soil structure.

2.3 Soil Classification Systems

2.3.1 Principles and purpose of soil classification

Soil classification is the systematic arrangement of soils into groups based on their observable, measurable properties, with the aim of organising soil knowledge so that information about one soil can be applied to predict the behaviour of similar soils elsewhere. A well-designed classification system is based on **diagnostic horizons** (horizons with specific, quantitatively defined properties that reflect the dominant pedogenic processes), **diagnostic properties** (specific physical or chemical characteristics of the soil material itself, such as aquic moisture regime, abrupt textural change, or certic properties), and **other criteria** such as moisture and temperature regimes.

The two most widely used international soil classification systems are USDA Soil Taxonomy (developed by the United States Department of Agriculture and widely used in Africa, the Americas, and for academic research) and the FAO/UNESCO World Reference Base for Soil Resources (WRB), which is used internationally and by FAO-supported survey programmes. Both systems use diagnostic horizons and properties to classify soils into hierarchical groups at multiple levels of detail. In Nigeria, older surveys used the FAO-UNESCO Soil Map of the World classification; more recent surveys and research publications use USDA Soil Taxonomy, with WRB increasingly used for international reporting.

Fill in the blank: Soil classification is based on ________ horizons and properties that have specific, quantitatively defined characteristics reflecting the dominant pedogenic processes.

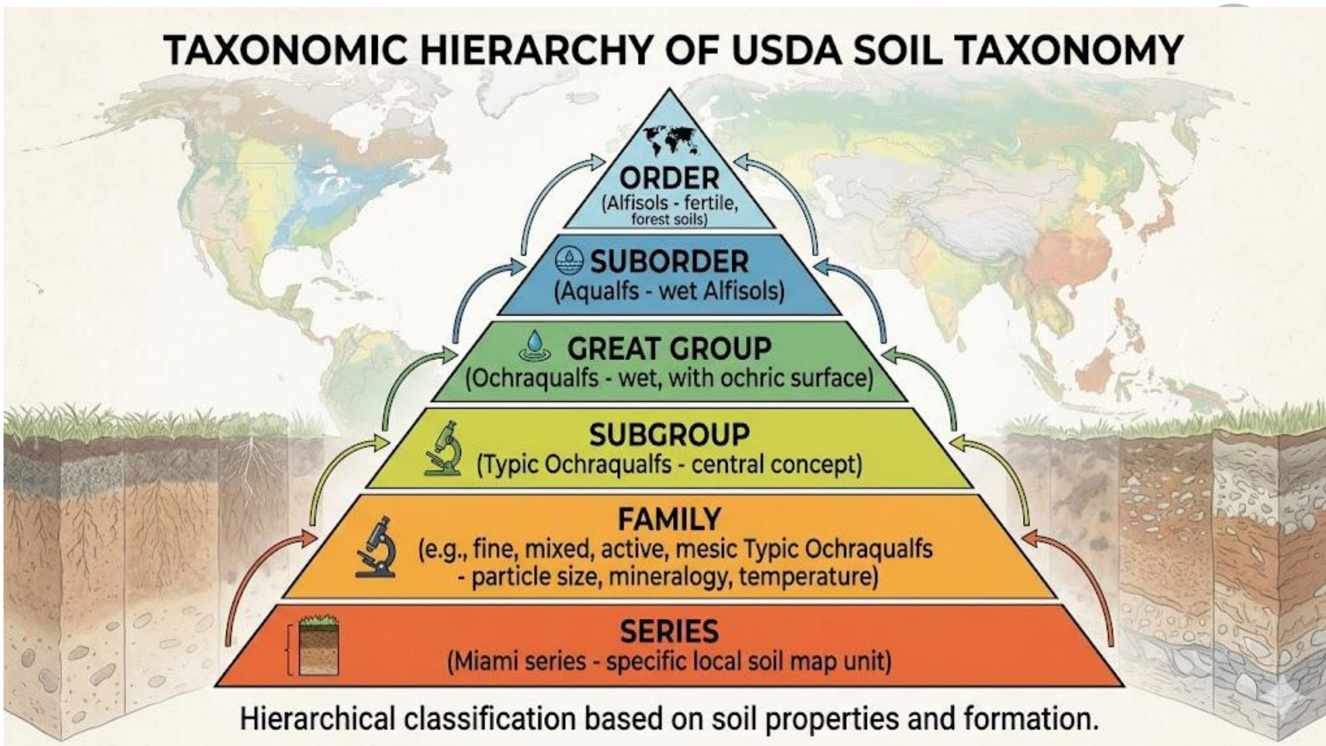

Figure 2.4: Diagram showing the hierarchical structure of USDA Soil Taxonomy from Order to Series

2.3.2 USDA Soil Taxonomy

USDA Soil Taxonomy organises soils into 12 orders at the highest level, distinguished by the presence or absence of specific diagnostic horizons and properties. The most important orders for Nigerian agriculture are: **Oxisols** (highly weathered, iron and aluminium oxide-rich soils with oxic horizons; very low fertility; dominant in humid forest zones), **Ultisols** (strongly leached, argillic B horizon, low base saturation; common in derived savanna and forest zones), **Alfisols** (moderately leached with argillic B horizon and moderate base saturation; common in Guinea and Sudan savanna and among the most agriculturally productive soils in Nigeria), and **Entisols** (weakly developed soils with minimal horizon differentiation; young soils on alluvial deposits or sandy parent materials).

Other important Nigerian soil orders include Inceptisols (young soils with limited profile development, common on recent alluvium and in areas of moderate relief), Vertisols (very high clay soils that shrink and crack deeply on drying, forming distinctive self-mulching surface and deep slickensided subsurface; common in some parts of the north where parent materials are rich in smectite clay minerals), and Aridisols (dry soils of the semi-arid far north with accumulation of calcium carbonate and salts). Each order implies specific management requirements: Oxisols need heavy phosphorus and lime inputs; Alfisols respond well to moderate fertilisation; Vertisols require special tillage equipment and timing; Entisols on flood plains may be highly productive but require drainage management.

Fill in the blank: ________ are among the most agriculturally productive soils in Nigeria, with moderately leached argillic B horizons and moderate base saturation, common in the Guinea and Sudan savanna zones.

Soil Order	**Diagnostic Horizon**	**Distribution in Nigeria**	**Fertility Status**	**Management Needs**
Oxisols	Oxic horizon (deep, highly weathered)	Humid tropics, southern Nigeria	Low fertility; leached, acidic	Liming, organic matter addition, fertilizer inputs
Ultisols	Argillic horizon (clay accumulation)	Southeastern Nigeria	Low fertility; acidic, nutrient-poor	Liming, balanced fertilization, erosion control
Alfisols	Argillic horizon with higher base saturation	Central and southwestern Nigeria	Moderate fertility; good moisture retention	Crop rotation, moderate fertilization, erosion management
Entisols	No diagnostic horizon (young soils)	River valleys, floodplains	Variable fertility; often fertile alluvium	Flood control, careful tillage, organic matter maintenance
Vertisols	Slickensides, high shrink-swell clays	Northern Nigeria (Sudan/Sahel zones)	High fertility but difficult to manage	Timing of tillage, drainage, crop selection for heavy soils

Inceptisols	Cambic horizon (weakly developed)	Highland areas, transitional zones	Moderate fertility; variable	Soil conservation, moderate fertilization, erosion control

Table 2.4: Major USDA Soil Taxonomy orders found in Nigeria with their diagnostic properties, distribution zones, and agricultural characteristics

2.3.3 FAO World Reference Base and Nigerian soil classification

The FAO World Reference Base for Soil Resources (WRB) is the international reference classification endorsed by the International Union of Soil Sciences. It uses a two-level system: 32 Reference Soil Groups (RSGs) at the first level, and qualifiers (prefix and suffix qualifiers) at the second level to provide additional detail. The RSGs most commonly encountered in Nigerian soils are: **Ferralsols** (equivalent to Oxisols; highly weathered, iron-rich, low-fertility), **Acrisols** (equivalent to Ultisols; clay-enriched subsoil with low base saturation), **Lixisols** (equivalent to Alfisols; clay-enriched subsoil with high base saturation), and **Fluvisols** (alluvial soils, equivalent to alluvial Entisols).

Additional important WRB groups in Nigeria include Plinthosols (soils with plinthite; major constraint in many southern Nigerian landscapes), Gleysols (waterlogged soils of valley bottoms and seasonally flooded areas), Vertisols (shrink-crack clays, same name as Soil Taxonomy), and Arenosols (sandy soils of the northern dry zones). The older Nigerian land classification system used in government land surveys divided soils into soil series based on profile morphology and parent material; these series remain in use in many existing survey reports and land evaluation documents. Understanding both the WRB and Soil Taxonomy systems, and how they relate to the older series-based nomenclature, is essential for reading Nigerian soil survey literature across different time periods.

Fill in the blank: ________ in the WRB classification are equivalent to Alfisols in USDA Soil Taxonomy, characterised by clay-enriched subsoil with high base saturation, and are among the most agriculturally important soils in the Nigerian savanna.

USDA Soil Order	WRB Equivalent (Reference Soil Group)	FAO/UNESCO Name	Nigerian Distribution Zone
Oxisols	Ferralsols	Ferralsols	Humid tropics, southern Nigeria (rainforest belt)
Ultisols	Acrisols	Acrisols	Southeastern Nigeria (humid forest zones)
Alfisols	Luvisols/Nitisols	Luvisols	Central and southwestern Nigeria (derived savanna, forest-savanna transition)
Entisols	Fluvisols/Arenosols	Fluvisols	River valleys, floodplains (Niger, Benue, Cross River basins)
Vertisols	Vertisols	Vertisols	Northern Nigeria (Sudan and Sahel zones, e.g., Kano, Borno plains)
Inceptisols	Cambisols	Cambisols	Highland areas (Jos Plateau, Mambilla Plateau)

Table 2.5: Cross-reference between major USDA Soil Taxonomy orders, WRB Reference Soil Groups, and their occurrence in Nigeria

Pilot questions 2.3

1. Explain the purpose of soil classification and describe what diagnostic horizons are.
2. Name four USDA Soil Taxonomy orders found in Nigeria and state the key distinguishing characteristic of each.
3. What are Alfisols and why are they considered among the most agriculturally productive soils in Nigeria?
4. Explain what Vertisols are and describe the management challenges they present.
5. State the WRB equivalents of Oxisols, Ultisols, and Alfisols.

2.4 Soil Survey

2.4.1 Purpose and types of soil survey

Soil survey is the systematic examination, description, classification, and mapping of soils in an area of land, with the purpose of providing information for land use planning, agricultural development, engineering design, environmental management, and scientific research. Soil survey produces maps showing the distribution of different soil types and reports describing their properties, agricultural suitability, and management requirements.

Soil surveys are classified by their intensity: detailed surveys (1:5,000 to 1:20,000 scale) map individual soil series and phases on a field-by-field basis, providing the most precise information for farm planning and engineering; semi-detailed surveys (1:20,000 to 1:50,000) provide information suitable for estate-level planning and irrigation scheme design; reconnaissance surveys (1:100,000 to 1:250,000) cover large areas with less detail, suitable for regional land use planning and identifying areas for more detailed investigation; broad-scale surveys (1:500,000 and smaller) provide national or continental overview information for policy and strategic planning. In Nigeria, the Federal Surveys Department and state governments have produced soil maps at various scales, with the most comprehensive coverage at the reconnaissance scale.

Fill in the blank: Detailed soil surveys at scales of 1:5,000 to 1:20,000 map individual soil ________ and phases on a field-by-field basis, providing the most precise information for farm planning.

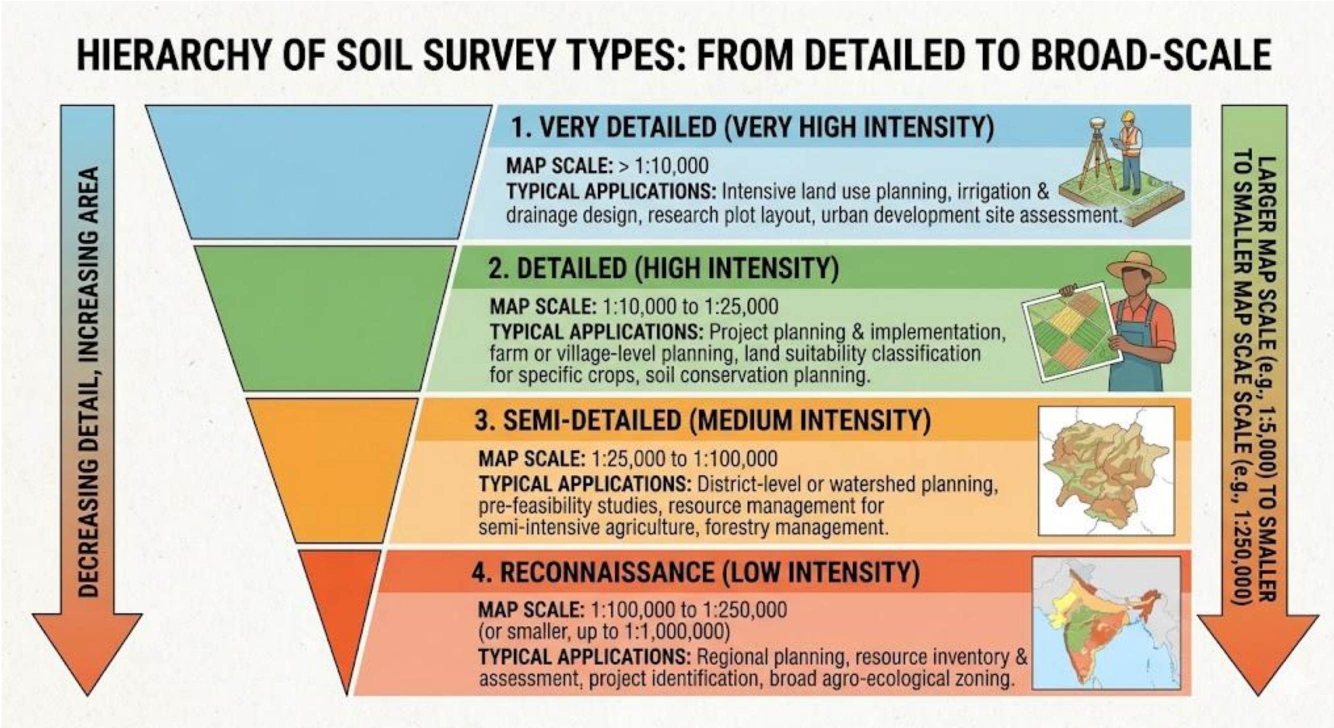

Figure 2.5: Diagram showing the hierarchy of soil survey types from detailed to broad-scale with their typical map scales and applications

2.4.2 Soil survey methods and mapping units

Soil survey methodology involves three stages: pre-field preparation, field survey, and report compilation. In the pre-field stage, existing maps, satellite imagery, air photographs, geological maps, and climate data are studied to identify the landscape units likely to contain different soil types. In the field stage, surveyors examine soil profiles at systematic or random sampling points (augering or pit digging), describe each profile using standardised morphological criteria, and collect samples for laboratory analysis. Observations are located by GPS and recorded on base maps or digital data capture devices.

Soil mapping units are the areas of land shown on a soil map as having a specific combination of soil types. A soil series is the most detailed unit, defined by a specific profile morphology, texture, and parent material developed under similar climate and vegetation. A soil phase is a subdivision of a series based on a surface characteristic (erosion phase, slope phase, stoniness phase) relevant to land use. Complex and association mapping units are used when two or more soil series occur in such intimate spatial association that they cannot be separated at the survey scale; an association names the dominant series in order of dominance. At reconnaissance scale, large mapping units (land systems or soil landscape units) are used, each encompassing multiple series across a defined landscape unit.

Fill in the blank: A soil ________ is the most detailed soil survey mapping unit, defined by a specific profile morphology, texture, and parent material developed under similar climate and vegetation.

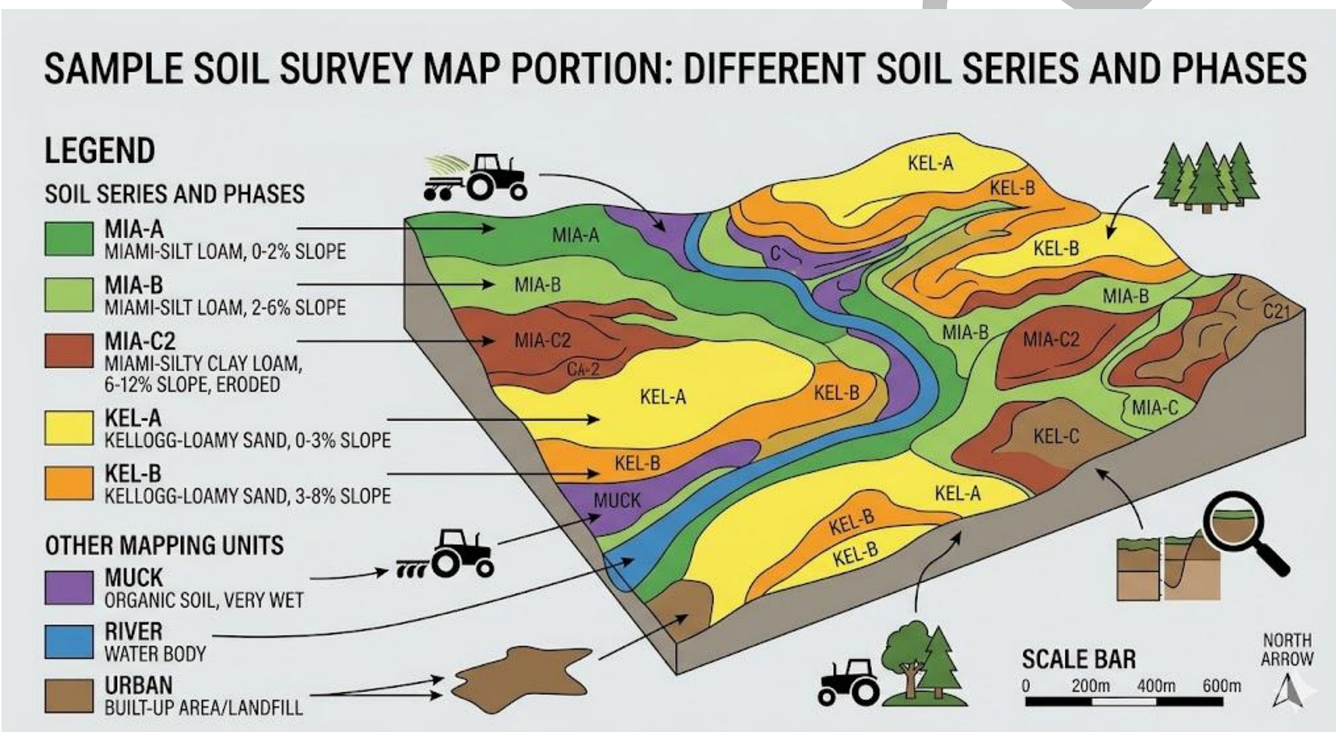

Figure 2.6: Example portion of a soil map showing soil series and phase mapping units with a legend and scale bar

2.4.3 Using soil survey information for agricultural planning

Soil survey information is applied to agricultural planning through land evaluation — the process of assessing the suitability of land for specific uses based on its soil and landscape properties. The FAO Land Evaluation Framework (1976) provides the standard methodology: land is assessed for a specific land use (e.g. rain-fed maize production, irrigated rice, tree crops) by comparing the land's properties with the requirements of the land use, and classified into land suitability classes from S1 (highly suitable, with no significant limitations) through S2 (moderately suitable, with limitations that reduce productivity) and S3 (marginally suitable, with major limitations) to N (not suitable for the specified use).

In Nigeria, soil survey information has been used to identify land suitable for large-scale irrigation schemes (Kano River Project, Bakolori, Hadejia Valley), to plan resettlement schemes, to assess the agricultural potential of new land development areas, and to guide fertiliser recommendations by identifying the dominant soil types and their nutrient-supplying capacity. At the farm level, soil survey maps allow a farm manager to identify which fields need drainage, which are suitable for deep-rooted crops, which have plinthite that limits deep cultivation, and which have high erosion risk requiring protective practices. Students should be able to read a soil survey report and extract the information needed to plan management of a specific parcel of land.

Fill in the blank: The FAO Land Evaluation Framework classifies land into suitability classes from S1 (highly suitable) through S2 and S3 to N (not ________ for the specified land use).

Step	Action	Details
Obtain soil map	Acquire the official soil survey report and maps for your area	Usually available from agricultural extension services, research institutes, or government agencies
Read series descriptions	Study the soil series and classification notes	Includes texture, depth, drainage, fertility, and limitations
Identify land units	Match your farm location to the mapped soil units	Helps determine which soil types are present on your land
Translate properties	Interpret soil characteristics into practical implications	For example, drainage issues → need for raised beds; low fertility → fertilizer planning
Develop management recommendations	Use survey data to guide cropping, irrigation, and conservation	Aligns soil capability with crop choice, fertilizer use, and erosion control

Box 2.1: Steps in using a soil survey report for agricultural planning on a Nigerian farm

Pilot questions 2.4

1. Define soil survey and state two purposes for which it is conducted.
2. Distinguish between detailed and reconnaissance soil surveys in terms of scale and application.
3. Describe the three stages of soil survey methodology.
4. Define a soil series and a soil phase and explain how they differ.
5. Explain how soil survey information is used in land evaluation for agricultural planning.

Series Summary

This Series has covered the physical properties of soil and the classification and survey systems through which soil knowledge is organised for practical use. We began with soil texture, defining the three soil separates (sand, silt, and clay) and their size ranges, explaining how the textural triangle is used to determine textural class, and describing how texture influences water-holding capacity, drainage, aeration, nutrient retention, tillage behaviour, and erosion susceptibility. We then examined soil structure, describing its types (granular, blocky, prismatic, platy), grades (structureless to strong), and sizes, and explaining how structure modifies soil behaviour and how management practices can build or destroy it.

Following that, we covered soil consistence and colour, explaining the moisture-state consistence descriptions and the meaning of soil colour in terms of organic matter content, iron oxide accumulation, and drainage conditions. We then introduced soil classification, explaining diagnostic horizons and the principles of classification, describing the major USDA Soil Taxonomy orders present in Nigeria (Oxisols, Ultisols, Alfisols, Entisols, Vertisols), and cross-referencing these with the WRB system. Finally, we covered soil survey — the types and scales, the three-stage methodology, the mapping units from soil series to land system, and the use of soil survey data in land evaluation and agricultural planning. By completing this Series, you should now be able to achieve all nine Series Learning Outcomes (SLO 2.1 to SLO 2.9).

Glossary of Terms

- **Acrisol:** WRB Reference Soil Group equivalent to USDA Ultisols; characterised by a clay-enriched argillic subsoil with low base saturation; common in the Nigerian derived savanna and forest zones.
- **Alfisol:** USDA Soil Taxonomy order characterised by an argillic B horizon with moderate to high base saturation; moderately productive soils common in the Nigerian Guinea and Sudan savanna.
- **Argillic horizon:** a diagnostic B horizon with a significant accumulation of clay translocated from overlying horizons by illuviation; characterised by clay films (cutans) on ped faces and pore walls.
- **Arenosol:** WRB Reference Soil Group equivalent to sandy Entisols; coarse-textured, low-fertility soils of the northern dry zones.
- **Cation exchange capacity (CEC):** the total capacity of a soil to hold exchangeable positively charged ions (cations) at a given pH; measured in centimoles of charge per kilogram (cmolc/kg); increases with clay and organic matter content.
- **Diagnostic horizon:** a soil horizon with specific, quantitatively defined physical and chemical properties used to classify soils in systematic classification systems such as USDA Soil Taxonomy and the WRB.
- **Entisol:** USDA Soil Taxonomy order for weakly developed soils with minimal horizon differentiation; found on young alluvial deposits, recent volcanic materials, and sandy parent materials in Nigeria.
- **Ferralsol:** WRB Reference Soil Group equivalent to Oxisols; highly weathered soils rich in iron and aluminium oxides, very low fertility; dominant in the humid forest zone.
- **Field feel test:** a method of estimating soil texture in the field by feeling the grittiness, silkiness, or stickiness of moistened soil and assessing its ability to form ribbons or balls.
- **Fluvisol:** WRB Reference Soil Group for alluvial soils developed on recent water-deposited sediments; equivalent to alluvial Entisols; often fertile but may require drainage management.
- **Gleyed soil:** a soil with grey, blue-grey, or olive colouration resulting from the chemical reduction of iron under anaerobic (waterlogged) conditions; indicates periodic or permanent waterlogging.

- **Land evaluation:** the process of assessing land suitability for specific land uses by comparing land properties with use requirements; the FAO Land Evaluation Framework provides the standard methodology.
- **Land suitability class:** a category in the FAO Land Evaluation Framework describing the suitability of land for a specified use: S1 (highly suitable), S2 (moderately suitable), S3 (marginally suitable), and N (not suitable).
- **Lixisol:** WRB Reference Soil Group equivalent to Alfisols; clay-enriched subsoil with high base saturation; among the most agriculturally important soils in the Nigerian savanna.
- **Oxisol:** USDA Soil Taxonomy order for the most highly weathered tropical soils, characterised by an oxic horizon rich in iron and aluminium oxides; very low inherent fertility; common in the humid forest zones.
- **Plinthosol:** WRB Reference Soil Group for soils with significant plinthite; common in many southern Nigerian landscapes; major limitation for deep cultivation and root crop production.
- **Reconnaissance survey:** a soil survey at 1:100,000 to 1:250,000 scale covering large areas with less detail than detailed surveys; suitable for regional land use planning and identifying priority areas for detailed investigation.
- **Soil series:** the most detailed mapping unit in soil classification, defined by a specific profile morphology, texture class, parent material type, and development under similar climate and vegetation conditions.
- **Soil texture:** the relative proportions of sand, silt, and clay particles in a soil; the most fundamental physical property determining water-holding capacity, drainage, nutrient retention, and tillage behaviour.
- **Textural class:** one of twelve standard USDA categories (sand, loamy sand, sandy loam, loam, silt loam, silt, sandy clay loam, clay loam, silty clay loam, sandy clay, silty clay, clay) defined by specific ranges of sand, silt, and clay percentages.
- **Textural triangle:** a triangular diagram with axes representing the percentages of sand, silt, and clay; used to determine the textural class of a soil from its particle size composition.
- **Ultisol:** USDA Soil Taxonomy order for strongly leached soils with argillic B horizon and low base saturation; common in the Nigerian derived savanna and forest-savanna transition zones.

- **Vertisol:** USDA Soil Taxonomy order (and WRB Reference Soil Group) for very high clay soils that shrink and crack deeply on drying and swell on wetting; require specialised tillage management; found in parts of the Nigerian north on smectite-rich parent materials.

Concept Check Questions [Series 2]

Objective Questions

1. Clay particles are smaller than ________ mm in diameter and carry a net negative surface charge. (Linked to SLO 2.1)
2. The ________ triangle is the standard diagram used to determine soil textural class from percentages of sand, silt, and clay. (Linked to SLO 2.2)
3. Well-developed soil structure creates ________ between aggregates that allow rapid water drainage and good aeration. (Linked to SLO 2.4)
4. ________ in USDA Soil Taxonomy are among the most agriculturally productive soils in Nigeria, common in the Guinea and Sudan savanna zones. (Linked to SLO 2.6)
5. The FAO Land Evaluation Framework classifies land into suitability classes from S1 (highly suitable) to N (not ________ for the specified use). (Linked to SLO 2.9)

Short-Answer Questions

1. Explain why clay particles have much higher cation exchange capacity than sand particles. (Linked to SLO 2.1)
2. Describe the four main types of soil structure and state where each is typically found in the soil profile. (Linked to SLO 2.4)
3. Explain what gleyed (grey, low-chroma) colours in a soil horizon indicate about the soil's formation environment. (Linked to SLO 2.5)
4. Name four USDA Soil Taxonomy orders found in Nigeria and state the key distinguishing property of each. (Linked to SLO 2.6)
5. Distinguish between a soil series and a soil phase as soil survey mapping units. (Linked to SLO 2.9)

Long-Answer Questions

1. Analyse the importance of soil texture to soil behaviour and management, explaining the properties of the three soil separates, how the textural triangle is used to classify texture, and how texture influences water-holding capacity, drainage, cation exchange capacity, tillage behaviour, and erosion susceptibility. (Linked to SLOs 2.1, 2.2, 2.3)
2. Discuss soil structure, consistence, and colour as physical properties used to describe and interpret soil profiles, explaining the types, grades, and sizes of structure; the consistence terms for dry, moist, and wet states; and the pedogenic significance of different soil colours. (Linked to SLOs 2.4, 2.5)
3. Evaluate soil classification and soil survey as systems for organising soil knowledge for agricultural use, describing the major Nigerian soil orders in USDA Soil Taxonomy and their WRB equivalents, explaining the types and methodology of soil survey, and describing how soil survey data are used in land evaluation for agricultural planning. (Linked to SLOs 2.6, 2.7, 2.8, 2.9)

Answers to Concept Check Questions [Series 2]

Objective Questions

1. 0.002.
2. Textural.
3. Macropores.
4. Alfisols.
5. Suitable.

Short-Answer Questions

1. Clay particles are smaller than 0.002 mm and consist of secondary clay minerals (kaolinite, smectite) with a crystalline layer structure that carries a permanent net negative surface charge on the layer surfaces and edges; this charge attracts and holds positively charged nutrient cations (Ca^{2+}, Mg^{2+}, K^+, NH_4^+) electrostatically at the clay surface, preventing them from leaching with percolating water; sand particles consist of primary minerals (quartz) with very little surface charge and therefore hold almost no exchangeable cations.

2. Granular and crumb: small, rounded, porous aggregates; found in biologically active, organic-matter-rich A horizons of well-managed soils. Blocky (angular and subangular): polyhedral blocks with flat to rounded faces; common in B horizons with clay accumulation. Prismatic and columnar: vertical columns; found in subsoils with high clay content and shrink-swell activity, particularly in Vertisols and some Alfisol B horizons. Platy: horizontal plates; found in compacted layers, tillage pans, and alluvial deposits.
3. Grey, blue-grey, and olive colours with low chroma (gleyed colours) indicate that the soil horizon has been subjected to prolonged or periodic waterlogging that created anaerobic (oxygen-depleted) conditions; under anaerobic conditions, soil bacteria use iron (Fe^{3+}, which is reddish-brown and insoluble) as an electron acceptor, reducing it to Fe^{2+} (which is soluble and colourless or pale grey); the reduced iron is leached away or redistributed, leaving the horizon with grey or bluish colours rather than the oxidised red-yellow colours of well-drained horizons.
4. Any four: Oxisols (highly weathered, oxic horizon rich in Fe and Al oxides, very low fertility); Ultisols (argillic B horizon, low base saturation, strongly leached); Alfisols (argillic B horizon, moderate to high base saturation, moderately productive); Entisols (minimal horizon differentiation, young soils on alluvium or sand); Vertisols (very high clay content, deep shrink-swell cracking on drying, slickensides in subsoil); Inceptisols (young soils with limited development, cambic B horizon).
5. A soil series is the most detailed soil survey mapping unit, defined by a complete set of profile characteristics including horizon sequence, texture of each horizon, structure, consistence, colour, parent material type, and mineralogy developed under similar climate and vegetation; it is given a place name (e.g. Egbeda series). A soil phase is a subdivision of a series based on a single surface characteristic that affects land use but does not change the basic series criteria, such as degree of erosion (eroded phase), surface slope class (sloping phase), or stoniness (stony phase); the series name is retained with the phase modifier added.

Long-Answer Questions

1. Basic response: Three separates: sand (0.05 to 2.0 mm, gritty, primary minerals, low CEC), silt (0.002 to 0.05 mm, silky, primary minerals, moderate CEC), clay (<0.002 mm, sticky, secondary clay minerals, high CEC with negative surface charge). Textural triangle: twelve classes from sand to clay; loam (23% clay, 28% silt, 52% sand) most productive. Texture effects: water-holding (clay highest total, sand highest proportion plant-available); drainage

(sand rapid, clay slow); CEC (clay highest, sand lowest); tillage (sand easy, clay difficult — hard when dry, plastic when wet); erosion (silt most erodible, clay forms stable aggregates).

2. Value-added response: The most practically important aspect of texture for Nigerian farmers is the interaction between clay content and soil moisture regime in determining the timing of tillage operations. Clay soils in the Guinea savanna have a very narrow window of workable moisture: too dry and the soil is rock-hard requiring excessive tractor draught; too wet and the soil is sticky and plastic, causing smearing and compaction. This workable window typically occurs only in the first days after the rains begin and at the drying phase after heavy rain events. Missing this window leads to either failed land preparation or soil structural damage. Understanding texture as the determinant of this window is the most directly actionable outcome of this part of the course for students who will advise farmers on mechanisation.
3. Basic response: Structure types: granular/crumb (A horizon, rounded porous), blocky (B horizon, angular/subangular), prismatic/columnar (subsoil, vertical), platy (compacted layers, horizontal). Grade: structureless (single-grain or massive), weak, moderate, strong. Structure effects on behaviour: macropores between aggregates allow drainage and aeration; well-structured clay drains faster than structureless clay; organic matter cements aggregates; compaction destroys macropores; cover crops and organic inputs build structure. Consistence: dry (loose to extremely hard), moist (friable = ideal tillage condition, firm), wet (stickiness and plasticity). Colour: dark A = organic matter; red-yellow B = iron oxide, oxidising conditions; grey = anaerobic, waterlogged; white = calcareous or siliceous.
4. Value-added response: Soil structure is the property that most clearly shows the effects of management decisions, and it is therefore the most sensitive indicator of whether a farming system is sustaining or degrading soil quality. A soil that entered cultivation with well-developed granular surface structure and is managed with continuous monocropping without organic matter returns will progressively lose its structure: organic matter content falls, the biological activity that creates aggregates declines, raindrop impact directly on the surface destroys surface aggregates, and a structural crust forms that reduces infiltration and increases runoff. Reconnecting structure maintenance (through organic matter additions, cover cropping, minimum tillage) to the visible long-term productive capacity of the land is the central practical message of this part of the course.
5. Basic response: USDA orders: Oxisols (oxic horizon, Fe/Al oxides, very low fertility, forest zone); Ultisols (argillic B, low base saturation, derived savanna); Alfisols (argillic B, moderate base saturation, Guinea and Sudan savanna, most productive); Entisols (minimal development, alluvium, sand); Vertisols (smectite clay, deep cracking, some northern areas);

Inceptisols (young, limited development). WRB: Oxisols = Ferralsols; Ultisols = Acrisols; Alfisols = Lixisols; alluvial Entisols = Fluvisols; Plinthosols (plinthite); Gleysols (waterlogged). Survey types: detailed (1:5,000 to 1:20,000, farm scale), semi-detailed (estate), reconnaissance (regional), broad (national). Mapping units: series (most detailed, profile morphology + parent material), phase (series + surface modifier), association (multiple series intimate mix). Land evaluation: FAO framework, S1 (highly suitable) to N (not suitable); match land properties to land use requirements.

6. Value-added response: The most underutilised resource in Nigerian agricultural development is the large body of soil survey data collected by the Federal Surveys Department and ADP programmes during the 1970s and 1980s. These surveys, though conducted at reconnaissance scale and using the older FAO-UNESCO classification, contain profile data, land suitability assessments, and management recommendations that remain largely valid today for the soils they described. Agriculture students who can read, interpret, and apply these existing survey reports — rather than waiting for new surveys that may never materialise — can make an immediate practical contribution to farm planning and extension work with the resources already available.

Answers to Pilot Questions [Series 2]

Part 2.1: Soil Texture

1. Sand: 0.05 to 2.0 mm; silt: 0.002 to 0.05 mm; clay: less than 0.002 mm (2 micrometres).
2. Clay particles consist of secondary clay minerals with a crystalline layer structure that carries a permanent net negative surface charge derived from isomorphous substitution within the crystal lattice and from broken bonds at crystal edges; this negative charge attracts and holds positively charged cations (plant nutrient ions) electrostatically, preventing them from leaching with percolating water; sand particles consist of primary minerals (predominantly quartz) with very little surface charge per unit mass and therefore hold almost no exchangeable cations.
3. Determine the percentage of sand, silt, and clay in the soil sample (by laboratory analysis using the hydrometer method or by field feel estimation); locate the percentage clay on the left axis, the percentage silt on the right axis, and the percentage sand on the bottom axis of the triangular diagram; draw lines parallel to each opposing side from each percentage point;

the point where all three lines intersect falls within a named textural class zone that is the textural class of the soil.

4. The field feel test: take a small soil sample, moisten to a workable consistency, and feel its texture while manipulating it between the fingers; sandy soil feels distinctly gritty when rubbed between fingers, will not form a coherent ball or ribbon, and falls apart when released; clay soil feels sticky and plastic when wet, can be moulded into balls and ropes, and forms a long (greater than 5 cm) smooth, shiny ribbon when pressed and squeezed between thumb and forefinger.
5. Loam combines approximately equal contributions from all three size fractions (approximately 23 per cent clay, 28 per cent silt, and 52 per cent sand), which means it has: sufficient clay for good water retention and moderate CEC to hold nutrients; sufficient sand for good drainage and aeration and relatively easy tillage; and sufficient silt for soil cohesion; this combination gives loam a wide workable moisture range, good water storage, acceptable CEC, and manageable tillage resistance that no single-fraction-dominated texture can match.

Part 2.2: Soil Structure, Consistence, and Colour

1. Granular and crumb: small, rounded, porous aggregates typically found in biologically active A horizons rich in organic matter. Blocky (angular and subangular): polyhedral aggregates with flat to irregular faces found in B horizons with clay accumulation. Prismatic and columnar: vertical columnar aggregates found in subsoils with high shrink-swell potential (Vertisols, some Alfisol B horizons). Platy: horizontal plate-like aggregates found in compacted layers (tillage pan), alluvial deposits, or fragipans.
2. Soil structure grade describes the degree of development and distinctness of aggregates; weak grade means the aggregates are poorly formed and barely distinguishable — they fall apart into single particles or powder when disturbed with minimal force; strong grade means the aggregates are very well-formed, durable, and clearly distinct from one another, separated by visible pores and planes of weakness, and resist breakdown even when the soil is disturbed with moderate force.
3. Friable moist consistence means the soil crumbles easily with moderate applied force when squeezed in the fist; it is considered the ideal condition for tillage because: the soil can be cut and moved by tillage implements without excessive draught; it crumbles into a fine tilth rather than smearing or compacting (as it would when too wet and plastic) or shattering into clods (as it would when too dry and hard); and seedbed preparation in this condition creates the fine, uniform tilth required for good seed-to-soil contact and uniform germination.

4. Gleyed grey, blue-grey, and olive colours with low chroma (typically 2 or less on the Munsell scale) in a soil horizon indicate that the horizon has experienced prolonged or periodic anaerobic (oxygen-depleted) conditions caused by waterlogging; under waterlogged conditions, iron (Fe^{3+}, reddish-brown and immobile) is reduced by soil bacteria to Fe^{2+} (soluble and mobile, which leaches away leaving grey colours); the abundance of grey mottles versus the background matrix colour, and their depth in the profile, indicate the frequency, duration, and depth of waterlogging.
5. Organic matter acts as a biological cement that binds mineral particles (sand, silt, clay) into stable aggregates: humic substances form bonds with clay mineral surfaces creating organo-mineral complexes; fungal hyphae physically enmesh mineral particles; bacterial polysaccharides glue particles together; earthworm casts are very stable aggregates cemented by mucus; the resulting aggregates are larger and more durable than single mineral particles alone, creating the macropores that allow rapid drainage and aeration in well-structured soils.

Part 2.3: Soil Classification Systems

1. Soil classification organises soils into groups based on measurable properties to allow information from one soil to predict the behaviour of similar soils elsewhere, guiding management, land evaluation, and fertiliser recommendations; diagnostic horizons are layers within the soil profile that have specific, quantitatively defined physical or chemical properties (such as a minimum clay increase, minimum base saturation, or specific mineralogy) that reflect the dominant pedogenic processes and are used to assign soils to classification categories.
2. Any four: Oxisols (oxic horizon; iron and aluminium oxide-dominated, extremely low fertility); Ultisols (argillic B horizon, base saturation less than 35 per cent, strongly leached); Alfisols (argillic B horizon, base saturation 35 per cent or more, moderately leached, agriculturally productive); Entisols (no diagnostic subsurface horizon, minimal profile development, young alluvial or sandy soils); Vertisols (very high smectite clay content, slickensides and deep cracking, self-mulching surface).
3. Alfisols are USDA Soil Taxonomy soils characterised by an argillic B horizon with moderate to high base saturation (greater than 35 per cent); they are among the most agriculturally productive Nigerian soils because they retain moderate levels of base cations (calcium, magnesium, potassium) despite significant leaching, supply adequate nutrients for staple crops without heavy lime applications, have reasonably good physical properties for tillage,

and are distributed across the most densely farmed Guinea and Sudan savanna zones where most of Nigeria's food crop production occurs.

4. Vertisols are soils with very high smectite clay content (typically greater than 30 per cent) that shrinks and cracks deeply (greater than 1 cm wide, greater than 50 cm deep) during dry seasons and swells shut when wetted; management challenges: very hard when dry making tillage extremely difficult; very sticky and plastic when wet making them almost untillable and impassable; deep cracking can damage plant roots; the narrow workable moisture window requires precisely timed tillage operations; special heavy equipment is needed; drainage management is often required because they drain slowly.
5. Oxisols = Ferralsols; Ultisols = Acrisols; Alfisols = Lixisols.

Part 2.4: Soil Survey

1. Soil survey is the systematic examination, description, classification, and mapping of soils in an area; two purposes: agricultural land use planning (identifying which soils are suitable for specific crops, irrigation, or drainage); engineering design (selecting appropriate sites and providing soil parameters for roads, buildings, and earthworks).
2. Detailed surveys (1:5,000 to 1:20,000): map individual soil series and phases with precise boundaries; appropriate for farm layout planning, irrigation design, and engineering site investigations. Reconnaissance surveys (1:100,000 to 1:250,000): cover large areas with broad mapping units (soil associations, land systems); appropriate for regional land use planning, identifying priority areas for more detailed investigation, and national resource assessment; much less field work per unit area, correspondingly less precision in boundary location and less specific management information.
3. Stage 1 — Pre-field preparation: compile existing geological, topographic, and land use maps; study satellite imagery and air photographs to identify landscape units likely to contain different soil types; design field sampling strategy. Stage 2 — Field survey: systematically examine soil profiles by augering or pit digging at planned sampling points; describe each profile using standardised morphological criteria; locate observations by GPS; collect soil samples for laboratory analysis; mark horizon boundaries on field maps or digital capture devices. Stage 3 — Report compilation: process laboratory data; classify soils by the chosen system; delineate mapping unit boundaries; write series descriptions and management interpretations; produce the soil map and accompanying report.
4. A soil series is the most detailed soil mapping unit, defined by a specific profile morphology (horizon sequence, depth, texture of each horizon, structure, colour, consistence), parent

material type, and development under similar climate and vegetation; it is named after a place near its type location (e.g. Egbeda series near Egbeda). A soil phase is a subdivision of a series based on a single surface or near-surface characteristic (erosion status, slope class, stoniness, flooding frequency) that is important for land use but does not change the fundamental series criteria; the phase modifier is appended to the series name.

5. Soil survey information is used in land evaluation through the FAO Land Evaluation Framework by: (1) identifying the soils present in the planning area from the soil map and series descriptions; (2) determining the relevant properties of each soil (drainage class, available water capacity, erosion hazard, fertility level, workability, slope); (3) comparing these properties against the requirements and limitations of the proposed land use (e.g. irrigated rice requires flat land, heavy texture, and good water retention; dryland maize requires well-drained soil, moderate to good fertility, and no severe erosion risk); (4) assigning each mapping unit to a land suitability class (S1, S2, S3, or N) for the proposed use; (5) generating management recommendations based on the identified limitations.

References and Attributions [Series 2]

Textual References (Books and External Sources)

- Brady, N. C., & Weil, R. R. (2016). The nature and properties of soils (15th ed.). Pearson Education.
- Soil Survey Staff. (1999). Soil taxonomy: A basic system of soil classification for making and interpreting soil surveys (2nd ed.). USDA Natural Resources Conservation Service.
- IUSS Working Group WRB. (2015). World reference base for soil resources 2014. International soil classification system for naming soils and creating legends for soil maps (update 2015). FAO.
- FAO (Food and Agriculture Organization of the United Nations). (1976). A framework for land evaluation. FAO Soils Bulletin No. 32. FAO.
- Juo, A. S. R., & Franzluebbers, K. (2003). Tropical soils: Properties and management for sustainable agriculture. Oxford University Press.
- FAO (Food and Agriculture Organization of the United Nations). (2025). Guidelines for sustainable agriculture. FAO.

Figures, Plates, Tables, and Boxes

- Table 2.1: USDA soil separates table Attribution: AI generated using prompt "Generate a table listing the three USDA soil separates: sand, silt, and clay, with diameter ranges, field feel, dominant minerals, and key properties." Suggested OER search string: "USDA soil separates sand silt clay size properties table OER".
- Figure 2.1: USDA soil textural triangle Attribution: AI generated using prompt "Generate a USDA soil textural triangle showing the twelve textural classes with percentage clay, silt, and sand axes clearly labelled." Suggested OER search string: "USDA soil textural triangle twelve classes sand silt clay OER diagram".
- Table 2.2: Sandy, loam, clay soil comparison table Attribution: AI generated using prompt "Generate a table comparing sandy soil, loam, and clay soil on water-holding capacity, drainage, aeration, CEC, tillage difficulty, and erosion susceptibility." Suggested OER search string: "soil texture properties sandy loam clay comparison water drainage CEC OER table".
- Figure 2.2: Soil structure types diagram Attribution: AI generated using prompt "Generate an illustrated diagram showing the four main soil structure types: granular, blocky, prismatic, and platy, with each type labelled." Suggested OER search string: "soil structure types granular blocky prismatic platy diagram OER".

- Table 2.3: Soil colour interpretation table Attribution: AI generated using prompt "Generate a table listing common soil colour groups with Munsell notation ranges and pedogenic significance including organic matter content, iron oxides, and drainage conditions." Suggested OER search string: "soil colour interpretation Munsell notation pedogenic significance table OER".
- Figure 2.3: Soil structure influence on soil behaviour Attribution: AI generated using prompt "Generate a four-panel diagram comparing well-structured and structureless soil on water infiltration, aeration, root penetration, and erosion resistance." Suggested OER search string: "soil structure influence infiltration aeration root penetration erosion OER diagram".
- Figure 2.4: USDA Soil Taxonomy hierarchy diagram Attribution: AI generated using prompt "Generate a hierarchical pyramid diagram showing the six levels of USDA Soil Taxonomy: Order, Suborder, Great Group, Subgroup, Family, and Series, with examples." Suggested OER search string: "USDA soil taxonomy hierarchical levels order suborder great group family series OER".
- Table 2.4: Nigerian soil taxonomy orders table Attribution: AI generated using prompt "Generate a table listing major Nigerian soil taxonomy orders including Oxisols, Ultisols, Alfisols, Entisols, Vertisols, and Inceptisols with diagnostic horizon, distribution, fertility, and management needs." Suggested OER search string: "Nigerian soil orders Alfisols Ultisols Oxisols Vertisols taxonomy table OER".
- Table 2.5: USDA-WRB soil classification cross-reference table Attribution: AI generated using prompt "Generate a cross-reference table showing major USDA soil orders, their WRB equivalents, FAO/UNESCO names, and Nigerian distribution zones." Suggested OER search string: "soil taxonomy WRB cross-reference Nigeria USDA FAO soil orders OER table".
- Figure 2.5: Soil survey types hierarchy diagram Attribution: AI generated using prompt "Generate a hierarchy diagram showing the four soil survey types from detailed to broad-scale with their map scales and typical applications." Suggested OER search string: "soil survey types hierarchy scales detailed reconnaissance broad OER diagram".
- Figure 2.6: Soil survey map example Attribution: AI generated using prompt "Generate an example soil survey map portion showing different soil series and phase mapping units with a legend and scale bar." Suggested OER search string: "soil survey map series phase mapping units legend scale bar OER".
- Box 2.1: Using a soil survey report for agricultural planning Attribution: AI generated using prompt "Generate a text box listing the steps for using a soil survey report for agricultural planning including obtaining the map, reading series descriptions, and translating to management

recommendations." Suggested OER search string: "using soil survey report agricultural planning farm management steps OER box".

Course code: AGE 202

Course title: Introduction to Soil Science

Course credit load: 2 Units

Series 3: Soil Colloids, Reactions, and Organic Matter

- **Part 3.1: Soil Colloids**
  - Sub Part 3.1.1: Nature and types of soil colloids
  - Sub Part 3.1.2: Properties of clay minerals
  - Sub Part 3.1.3: Cation exchange capacity and base saturation
- **Part 3.2: Soil Reactions (Soil pH)**
  - Sub Part 3.2.1: Definition and measurement of soil pH
  - Sub Part 3.2.2: Factors affecting soil pH
  - Sub Part 3.2.3: Effects of soil pH on nutrient availability and plant growth
- **Part 3.3: Soil Organic Matter**
  - Sub Part 3.3.1: Sources and composition of soil organic matter
  - Sub Part 3.3.2: Decomposition and mineralisation of organic matter
  - Sub Part 3.3.3: Functions of organic matter in soil fertility and structure
- **Part 3.4: Soil Organisms**
  - Sub Part 3.4.1: Categories and roles of soil organisms
  - Sub Part 3.4.2: Soil bacteria, fungi, and actinomycetes
  - Sub Part 3.4.3: Soil fauna and their role in soil health

Introduction

The chemical and biological dimensions of soil science — soil colloids, soil reactions, organic matter, and soil organisms — are less immediately visible than texture or structure but are equally determinative of soil productivity. The cation exchange capacity of the clay fraction holds the nutrients that feed crops; the pH of the soil solution controls whether those nutrients are available or locked away; organic matter simultaneously improves the physical, chemical, and biological properties of soil; and the soil organisms that decompose organic matter, cycle nutrients, and build soil structure are the biological engine that makes the whole system function.

The aim of this Series is to introduce you to the nature and properties of soil colloids, the concept of cation exchange and base saturation, the determinants and effects of soil pH, the composition and functions of soil organic matter, and the major groups of soil organisms and their roles in maintaining soil health and fertility.

We shall commence this Series by examining soil colloids and their properties. Next, we will study soil reactions and the management of soil pH. Following that, we will cover the sources, decomposition, and functions of soil organic matter. Finally, we will wrap up with the major categories of soil organisms and their contributions to soil function.

Series Learning Outcomes

Upon completing this Series, you should be able to:

- **SLO 3.1** define soil colloids and describe the types of colloids found in soil (Linked to Part 3.1),
- **SLO 3.2** describe the properties of the major clay mineral groups and explain how they differ in CEC and behaviour (Linked to Part 3.1),
- **SLO 3.3** define cation exchange capacity and base saturation and explain their importance to soil fertility (Linked to Part 3.1),
- **SLO 3.4** define soil pH, explain how it is measured, and describe the factors that cause soils to become acid or alkaline (Linked to Part 3.2),

- **SLO 3.5** explain the effects of soil pH on nutrient availability and describe the management of soil acidity and alkalinity (Linked to Part 3.2),
- **SLO 3.6** describe the sources and composition of soil organic matter and explain the process of decomposition (Linked to Part 3.3),
- **SLO 3.7** explain the physical, chemical, and biological functions of soil organic matter (Linked to Part 3.3),
- **SLO 3.8** identify the major categories of soil organisms and describe their general roles (Linked to Part 3.4), and
- **SLO 3.9** explain the specific roles of soil bacteria, fungi, actinomycetes, and soil fauna in soil nutrient cycling and structure (Linked to Part 3.4).

3.1 Soil Colloids

3.1.1 Nature and types of soil colloids

Soil colloids are the finest fraction of the soil, with particles smaller than 0.001 mm (1 micrometre) in at least one dimension. They are the chemically and electrostatically active fraction of the soil, possessing large surface area per unit mass and carrying surface charges that allow them to attract and exchange ions from the soil solution. Two major types of soil colloids are present in mineral soils: **inorganic colloids** (clay minerals and metal oxides/hydroxides of iron, aluminium, and manganese) and **organic colloids** (humus and other partially decomposed organic materials).

Clay minerals are crystalline aluminosilicate colloids formed from alternating layers of silica tetrahedral sheets and aluminium octahedral sheets; the arrangement of these layers determines the clay mineral type and its properties. Metal oxides (iron oxides such as haematite and goethite, aluminium hydroxides such as gibbsite) are abundant in highly weathered tropical soils and carry variable charge (positive at low pH, negative at high pH) rather than the permanent negative charge of clay minerals. Humus colloids carry a large amount of negative charge per unit mass (higher charge density than most clay minerals) and are the most chemically reactive organic fraction, profoundly influencing nutrient availability and soil structure.

Fill in the blank: Soil colloids are the finest soil fraction, smaller than ________ mm, and include clay minerals, metal oxides, and humus; they are the chemically active fraction that controls nutrient exchange in the soil.

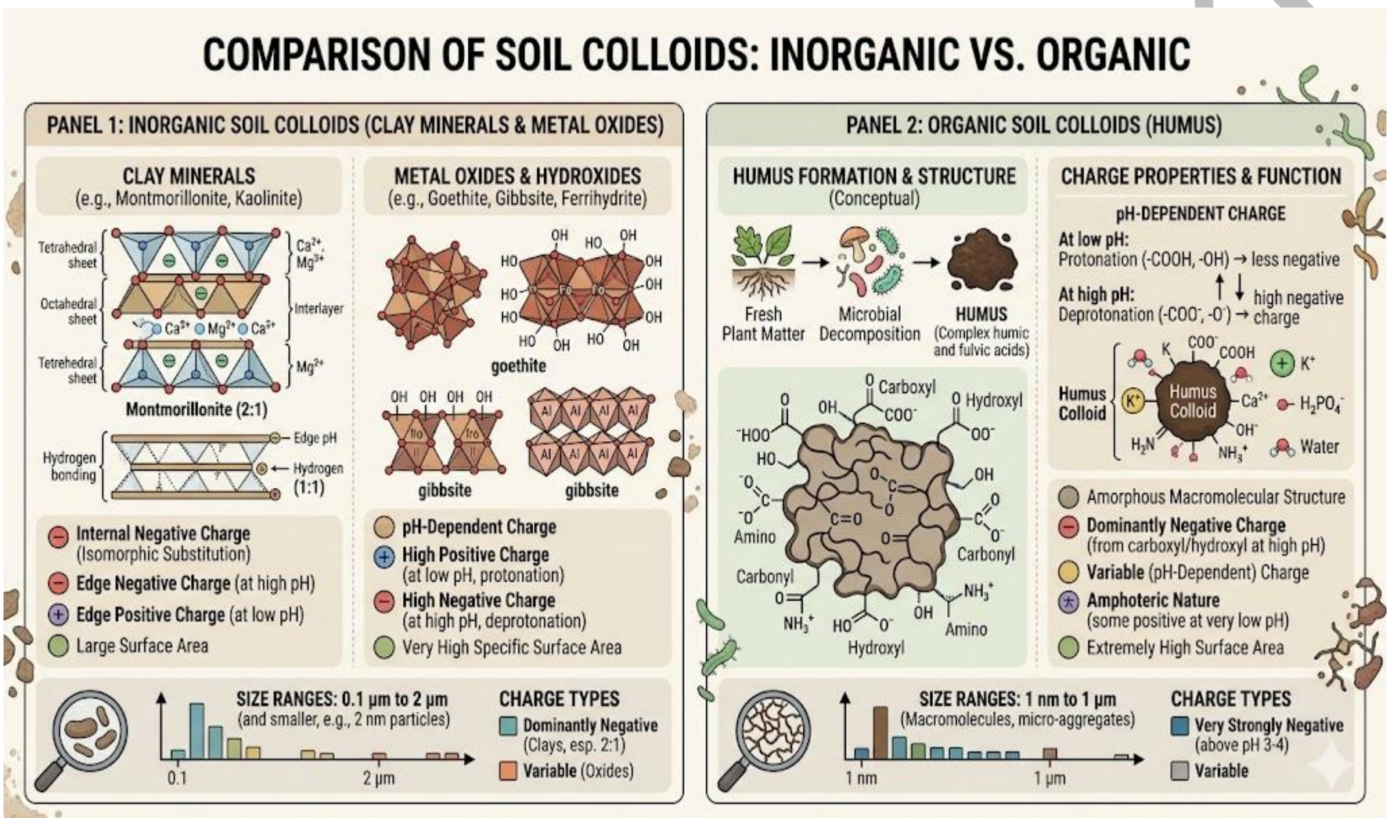

Figure 3.1: Diagram showing the two types of soil colloids (inorganic clay minerals and organic humus) and their charge characteristics

3.1.2 Properties of clay minerals

Clay minerals are classified by the ratio of silica tetrahedral sheets to aluminium octahedral sheets in their layer structure. **1:1 clay minerals** (kaolinite group) have one silica sheet to one aluminium sheet per layer; the layers are held together tightly by hydrogen bonds; there is minimal swelling when wetted; the CEC is low (3 to 15 cmolc/kg) and the surface area is relatively small. Kaolinite is the dominant clay mineral in highly weathered tropical soils including the Alfisols, Ultisols, and Oxisols that dominate Nigerian soil landscapes.

2:1 clay minerals have two silica sheets sandwiching one aluminium sheet. The most important 2:1 minerals are smectite (montmorillonite), illite, and vermiculite. Smectite has a large interlayer space that expands when water enters, giving it a very high CEC (80 to 150 cmolc/kg) and pronounced shrink-swell behaviour; it is the dominant clay in Vertisols. Illite has a moderate CEC (15 to 40 cmolc/kg) and limited expansion because potassium ions are fixed in the interlayer positions. Vermiculite has a high CEC (100 to 150 cmolc/kg) and moderate expansion. In Nigeria, smectitic clays occur in specific areas of the north and in some valley bottom alluvial deposits; their presence creates dramatically different management requirements from the kaolinite-dominated soils of most of the country.

Fill in the blank: ________ clay minerals (kaolinite group) have a 1:1 layer structure, low CEC of 3 to 15 cmolc/kg, and minimal swelling; they are the dominant clay in highly weathered Nigerian soils.

Clay Mineral	**Layer Structure**	**CEC (Cation Exchange Capacity)**	**Swelling Potential**	**Surface Area**	**Nigerian Occurrence**
Kaolinite	1:1 (one tetrahedral + one octahedral sheet)	Low (3–15 cmol/kg)	Very low	Small (~10–30 m²/g)	Common in humid southern Nigeria (Oxisols, Ultisols)
Smectite	2:1 (two tetrahedral + one octahedral sheet)	Very high (80–150 cmol/kg)	High (expands with water)	Large (~600–800 m²/g)	Found in Vertisols of northern Nigeria (Sudan/Sahel zones)
Illite	2:1 with K^+ interlayer bonding	Moderate (20–40 cmol/kg)	Low to moderate	Medium (~100–200 m²/g)	Occurs in sedimentary soils of central Nigeria
Vermiculite	2:1 with hydrated interlayers	High (100–150 cmol/kg)	Moderate	Large (~400–600 m²/g)	Present in weathered soils of savanna regions

Table 3.1: Comparison of major clay mineral types by layer structure, CEC, swelling, surface area, and Nigerian occurrence

3.1.3 Cation exchange capacity and base saturation

Cation exchange capacity (CEC) is the total capacity of a soil to hold exchangeable positively charged ions (cations) at a given pH; it is the sum of the exchange sites on clay minerals and humus per unit mass of soil, measured in centimoles of charge per kilogram (cmolc/kg). CEC is the most important single indicator of a soil's nutrient-holding ability: a soil with high CEC can retain large quantities of nutrient cations (Ca2+, Mg2+, K+, NH4+) against leaching; a soil with low CEC (sands, highly weathered tropical soils) rapidly loses applied fertiliser nutrients to leaching. The CEC of a soil increases with clay content, organic matter content, and the proportion of 2:1 clay minerals relative to 1:1 clays.

Base saturation is the percentage of the CEC occupied by basic cations (calcium, magnesium, potassium, and sodium) as opposed to acidic cations (hydrogen and aluminium). A soil with 100 per cent base saturation has all exchange sites occupied by Ca2+, Mg2+, K+, and Na+; it is fertile and has a neutral to alkaline pH. As base saturation falls (bases are leached away and replaced by H+ and Al3+), the soil becomes more acidic and less fertile. Base saturation below 35 per cent is the criterion that distinguishes Ultisols from Alfisols in USDA Soil Taxonomy. Liming a soil adds calcium and magnesium cations that displace H+ and Al3+ from exchange sites, raising pH and base saturation simultaneously.

Fill in the blank: ________ saturation is the percentage of CEC occupied by basic cations (Ca, Mg, K, Na); when it falls below 35 per cent (as bases are leached), soils become acidic and are classified as Ultisols.

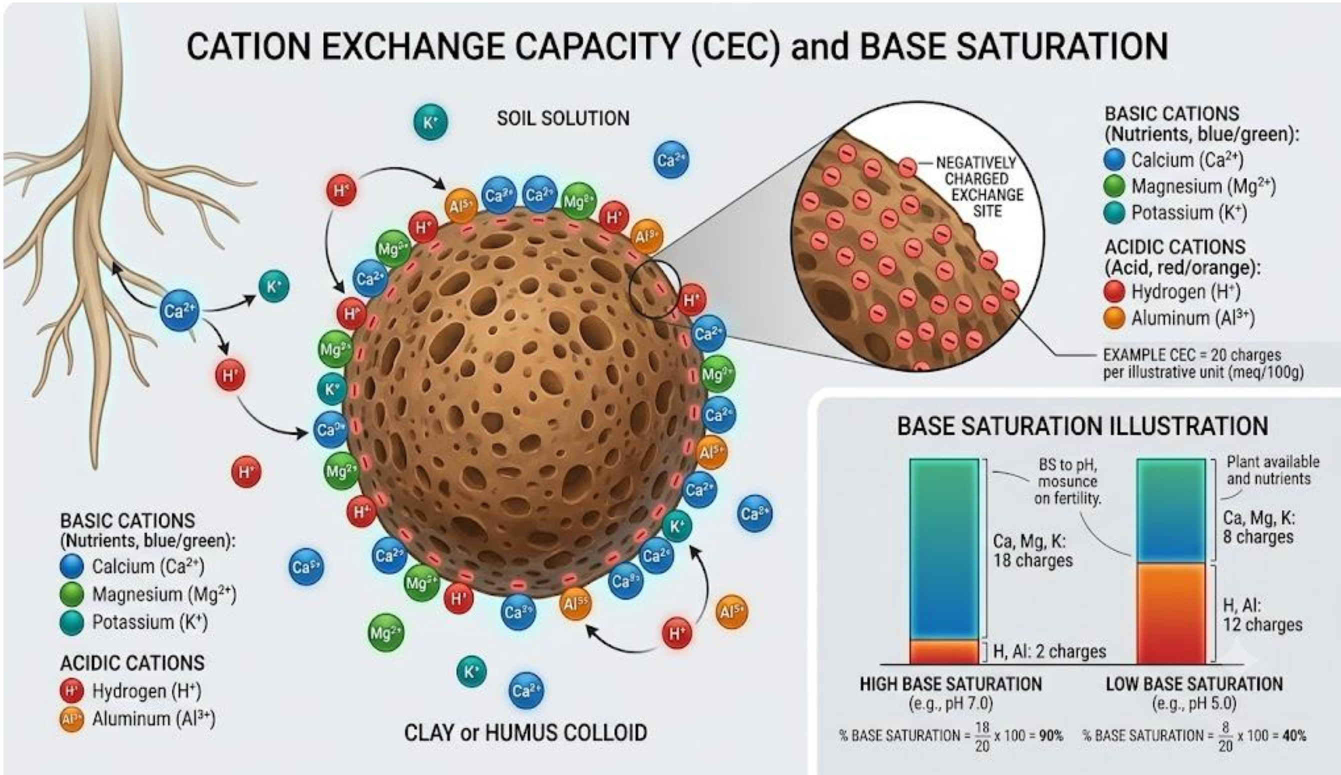

Figure 3.2: Diagram showing the concept of cation exchange capacity with exchange sites occupied by nutrient cations and hydrogen/aluminium ions

Pilot questions 3.1

1. Define soil colloids and state the two main types found in mineral soils.
2. Explain the difference between 1:1 and 2:1 clay minerals and give one example of each.
3. Why does kaolinite have a much lower CEC than smectite?
4. Define cation exchange capacity and explain why it is important for soil fertility.
5. Define base saturation and explain how liming increases base saturation.

3.2 Soil Reactions (Soil pH)

3.2.1 Definition and measurement of soil pH

Soil pH is the negative logarithm of the hydrogen ion activity (concentration) in the soil solution: pH = -log[H+]. At pH 7 (neutral), hydrogen ion and hydroxyl ion activities are equal;

pH values below 7 indicate acidic conditions (more H+ than OH-); values above 7 indicate alkaline (basic) conditions (more OH- than H+). Because pH is a logarithmic scale, a change of one pH unit represents a tenfold change in H+ concentration: a soil at pH 5 is ten times more acidic than one at pH 6, and one hundred times more acidic than one at pH 7.

Soil pH is measured using a pH meter with a glass electrode and a reference electrode immersed in a 1:1 or 1:2.5 soil-to-water suspension (or a 0.01 M CaCl2 solution for more reproducible results). Indicator papers and colorimetric test kits provide less precise but rapid field estimates. The active pH measured in the soil solution reflects only the H+ in solution; the reserve acidity — the much larger pool of H+ and Al3+ ions held on exchange sites — is not measured by pH alone. The total acidity (active plus reserve) is important for liming calculations; it is measured by buffer pH tests or by titration methods that displace the exchangeable acid cations.

Fill in the blank: Soil pH is the negative ________ of the hydrogen ion activity in the soil solution; at pH 7 the soil is neutral, below 7 acidic, and above 7 alkaline.

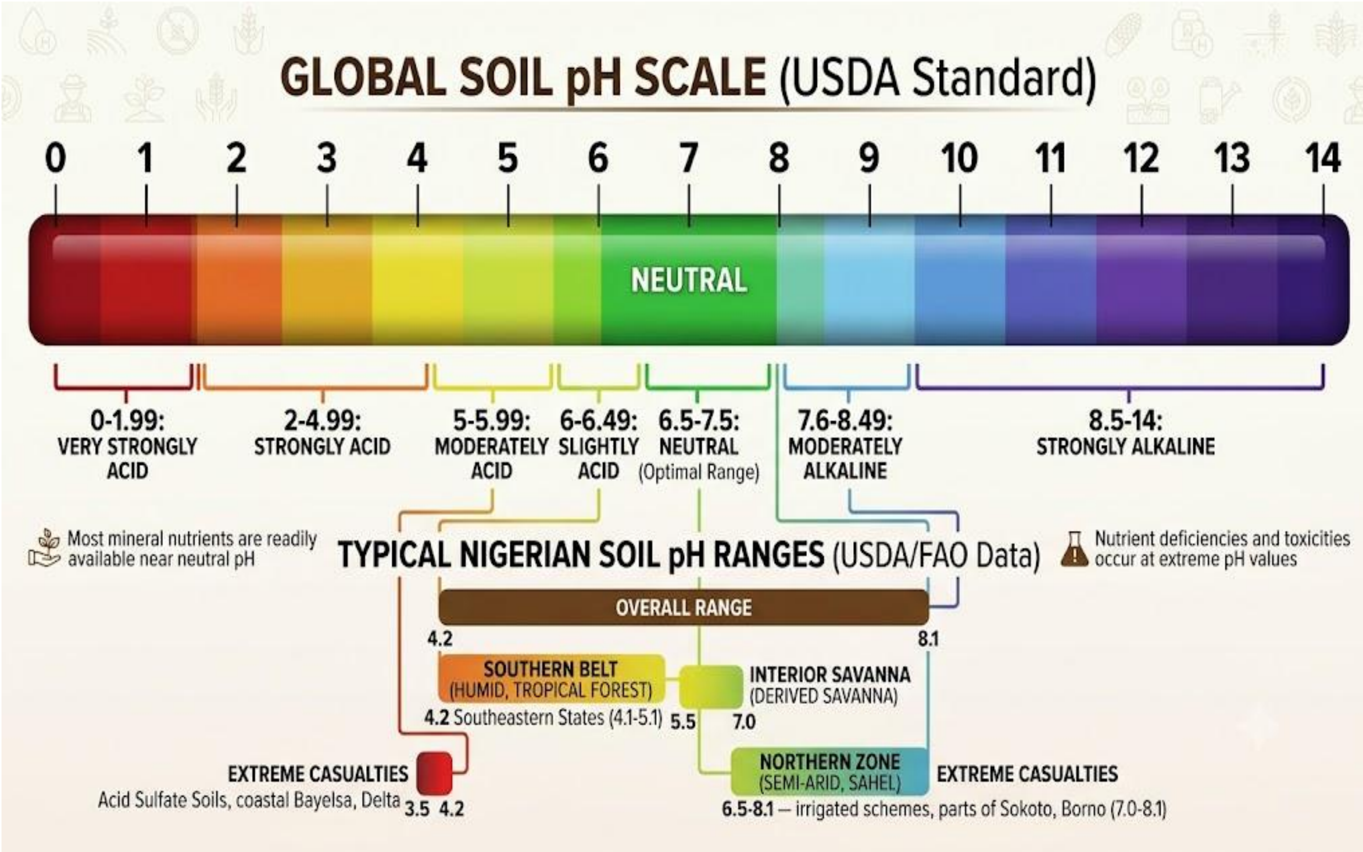

Figure 3.3: pH scale from 0 to 14 showing the pH ranges of common soil conditions and Nigerian soil types

3.2.2 Factors affecting soil pH

Soil pH is determined by the balance between acid-forming and base-forming processes and is influenced by: **parent material** (rocks rich in calcium and magnesium carbonate produce calcareous, alkaline soils; siliceous, calcium-poor rocks weather to acidic soils); **rainfall and leaching** (high rainfall leaches base cations from the profile, allowing H+ and Al3+ to occupy exchange sites, lowering pH; this is why humid tropical soils are strongly acidic); **organic matter decomposition** (releases organic acids and carbonic acid, contributing to natural soil acidification); and **fertiliser applications** (ammonium-based nitrogenous fertilisers such as urea and ammonium sulphate are strongly acidifying because nitrification releases H+ for every ammonium ion converted to nitrate).

In Nigeria, soil acidity is the most widespread soil chemical constraint on crop production: most soils in the humid forest and derived savanna zones have pH values between 4.5 and 6.0, and many have aluminium toxicity as a major growth-limiting factor. Alkaline soils occur in the semi-arid north where calcium carbonate accumulates in the dry season due to upward capillary movement of water; and in irrigated areas where poor irrigation water quality or excessive evaporation has caused secondary salinisation. Sodic soils (high sodium, pH above 8.5) restrict infiltration and are physically unstable; they require gypsum treatment and controlled irrigation to reclaim.

Fill in the blank: High rainfall and leaching lower soil pH by removing ________ cations from exchange sites and allowing H+ and Al3+ to dominate, making humid tropical soils typically strongly acidic.

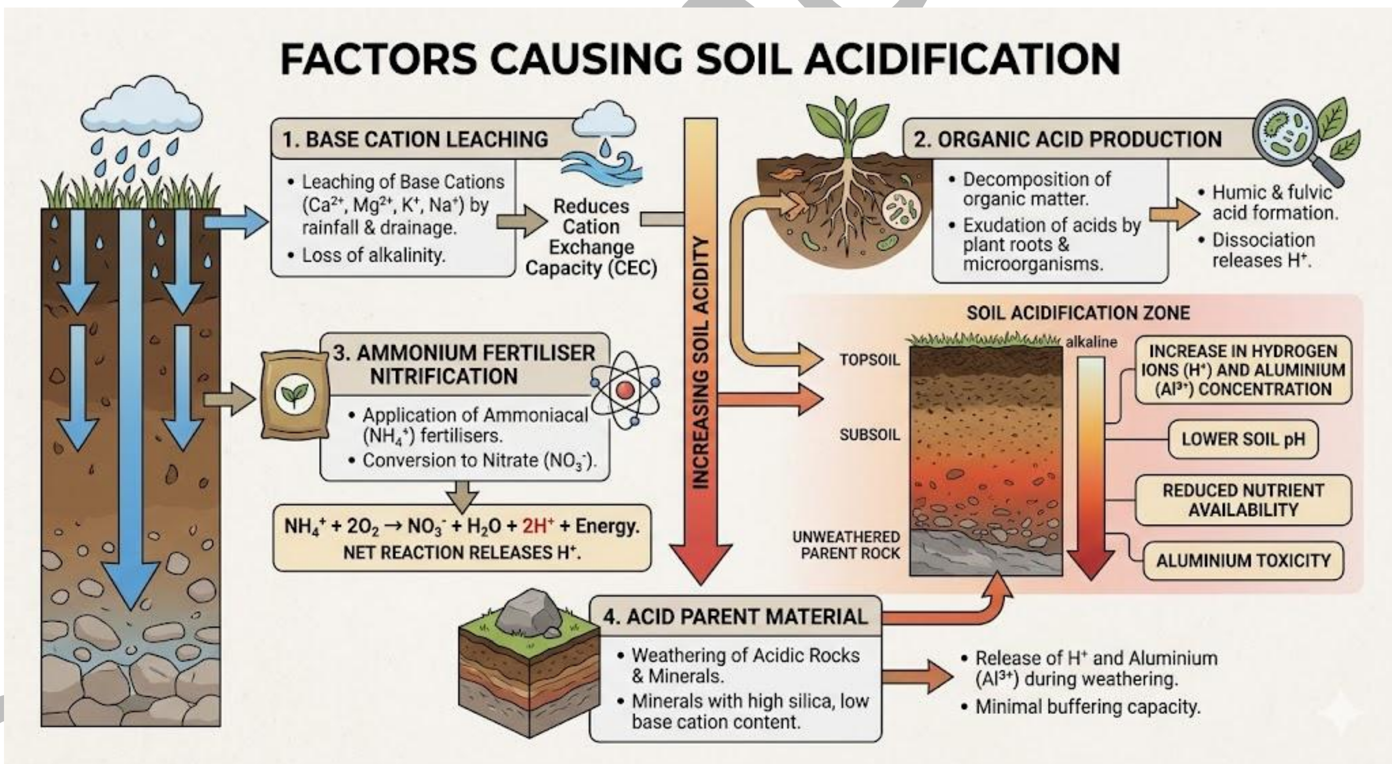

Figure 3.4: Diagram showing the factors that cause soil acidification including rainfall/leaching, organic matter decomposition, and ammonium fertiliser nitrification

3.2.3 Effects of soil pH on nutrient availability and plant growth

Soil pH controls nutrient availability by determining the chemical form and solubility of nutrient elements. Most macronutrients (nitrogen, phosphorus, potassium, calcium, magnesium, sulphur) are most available between pH 6.0 and 7.5. At low pH (below 5.5): phosphorus availability decreases because phosphate ions are fixed by iron and aluminium oxides; molybdenum becomes deficient; and aluminium and manganese solubility increases dramatically, causing direct toxicity to plant roots and interfering with calcium uptake. At high pH (above 7.5): iron, zinc, copper, manganese, and boron become insoluble and deficient; phosphorus is fixed by calcium.

The most practically important consequence of low pH in Nigerian soils is aluminium toxicity: at pH below 5.0, $Al3+$ ions are sufficiently soluble to inhibit root elongation, impair nutrient uptake, and cause severe yield reductions in sensitive crops. Rice and cassava are relatively tolerant of acidity; maize, cowpea, and soybean are moderately sensitive; many vegetables are highly sensitive. Soil acidity management by liming (applying ground limestone — calcium carbonate — at rates calculated from the lime requirement test) raises pH, reduces aluminium toxicity, supplies calcium, and improves the availability of phosphorus and most micronutrients. In Nigeria, widespread soil acidity means that lime application is one of the most economically justifiable soil amendments for many farming systems, yet remains underused because of limited farmer awareness.

Fill in the blank: At soil pH below 5.0, ________ toxicity becomes the primary nutrient constraint to plant growth, inhibiting root elongation and impairing nutrient uptake in sensitive crops.

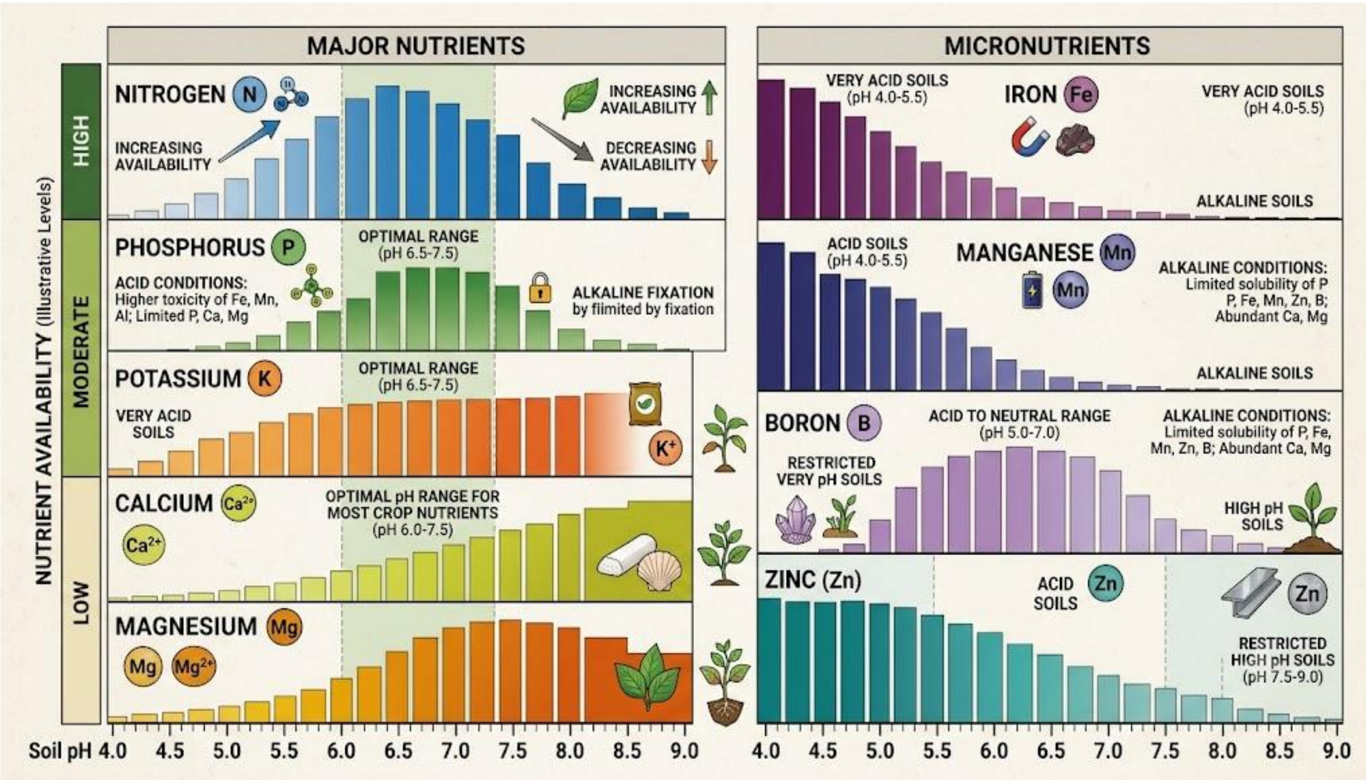

Figure 3.5: Diagram showing nutrient availability as a function of soil pH from 4.0 to 9.0

Pilot questions 3.2

1. Define soil pH and explain what is meant by the logarithmic nature of the pH scale.
2. Explain why high rainfall soils in humid Nigeria are typically strongly acidic.
3. Explain why ammonium-based fertilisers acidify the soil.
4. Describe the effect of low soil pH on phosphorus availability and aluminium toxicity.
5. Explain how liming corrects soil acidity and state two benefits of liming beyond pH correction.

3.3 Soil Organic Matter

3.3.1 Sources and composition of soil organic matter

Soil organic matter (SOM) is defined as the sum of all organic materials in the soil, including living organisms, fresh plant and animal residues, and the various stages of decomposed material from fresh litter to stable humus. The main sources of organic matter inputs to agricultural soils are: crop residues (roots, stubble, and leaves returned to the soil after harvest — the largest input in most farming systems), organic manures (farmyard manure, compost, poultry manure), root turnover and exudates from growing crops, weed and cover crop biomass, and atmospheric deposition of organic compounds.

Soil organic matter is composed of non-humic substances (cellulose, hemicellulose, starch, proteins, fats, and sugars that decompose relatively rapidly) and humic substances (humic acid, fulvic acid, and humin — large, complex, dark-coloured polymers resistant to rapid decomposition). Humic substances constitute the stable fraction of organic matter and are the primary contributors to the long-term cation exchange capacity, water retention, and structural stability associated with organic matter. In Nigerian agricultural soils, organic matter contents are generally low (0.5 to 2 per cent in cultivated soils of the savanna zone), making organic matter management one of the highest-priority interventions for sustaining soil productivity.

Fill in the blank: The stable fraction of soil organic matter consists of ________ substances (humic acid, fulvic acid, and humin), which are large, complex polymers resistant to rapid decomposition and responsible for long-term soil fertility benefits.

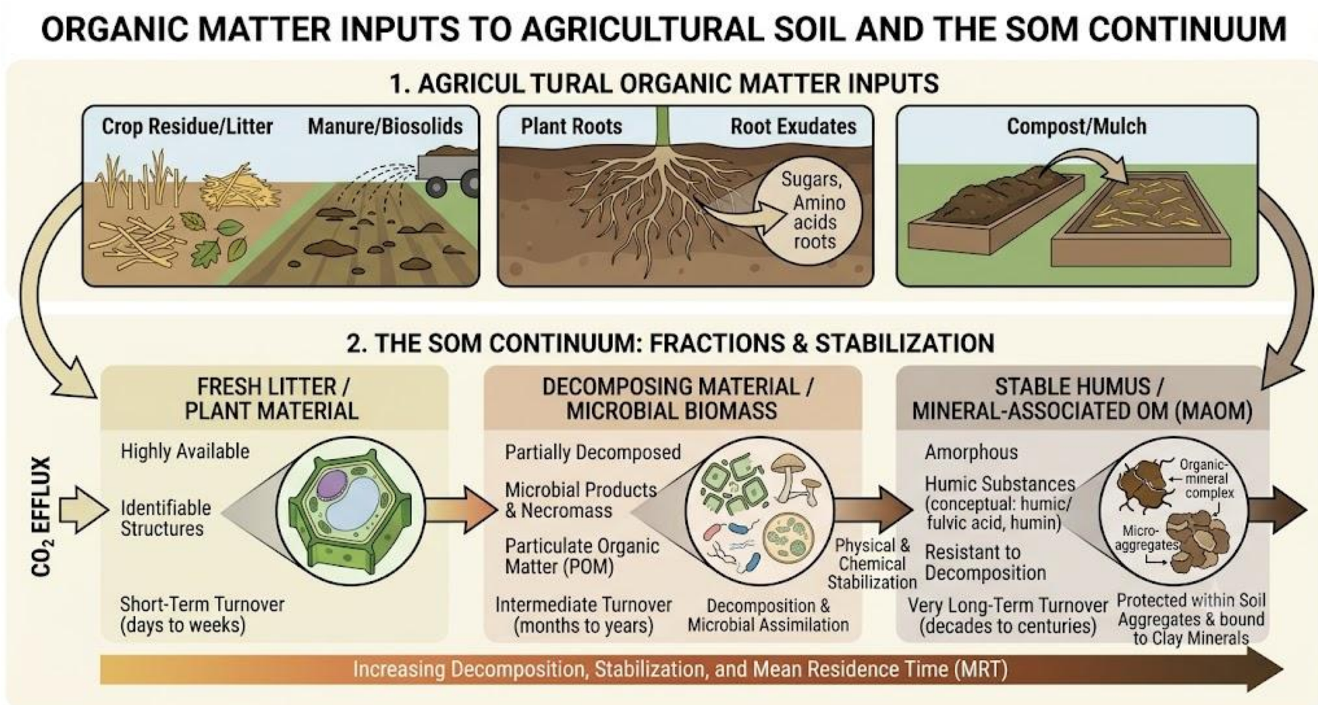

Figure 3.6: Diagram showing the sources of organic matter inputs to agricultural soil and the fractions of SOM from fresh residues to stable humus

3.3.2 Decomposition and mineralisation of organic matter

Decomposition is the biological breakdown of organic compounds by soil microorganisms, releasing carbon dioxide, water, and mineral nutrients. The rate of decomposition depends on: **temperature** (decomposition rate roughly doubles per 10°C increase; very slow in cold climates, rapid in warm tropical conditions — a major reason why organic matter accumulates in cool temperate soils but is rapidly decomposed in tropical soils); **moisture** (optimal decomposition requires adequate water; very dry and waterlogged conditions both slow decomposition); **aeration** (aerobic decomposition is much faster than anaerobic; waterlogged soils decompose slowly and may accumulate organic matter as peat); and the **C:N ratio of the residue** (low C:N materials like legume leaves decompose rapidly and release nitrogen; high C:N materials like cereal straw decompose slowly and temporarily immobilise soil nitrogen).

Mineralisation is the release of mineral nutrients (particularly nitrogen as ammonium and then nitrate, phosphorus as phosphate, sulphur as sulphate) from organic compounds during decomposition, making them available for plant uptake. The complement of mineralisation is immobilisation — the temporary incorporation of mineral nutrients into microbial biomass during the decomposition of high C:N ratio materials, which reduces the availability of those nutrients to plants. In Nigeria's warm climate, organic matter decomposes rapidly, meaning that large and frequent additions of organic materials are needed to maintain organic matter levels in cultivated soils. The ratio of organic carbon to nitrogen (C:N ratio) in crop residues is a key predictor of whether their decomposition will mineralise net nitrogen (low C:N, below 25:1) or temporarily immobilise it (high C:N, above 30:1).

Fill in the blank: The ________ ratio of organic residues predicts whether decomposition will release plant-available nitrogen (mineralisation, when the ratio is low) or temporarily tie it up in microbial biomass (immobilisation, when the ratio is high).

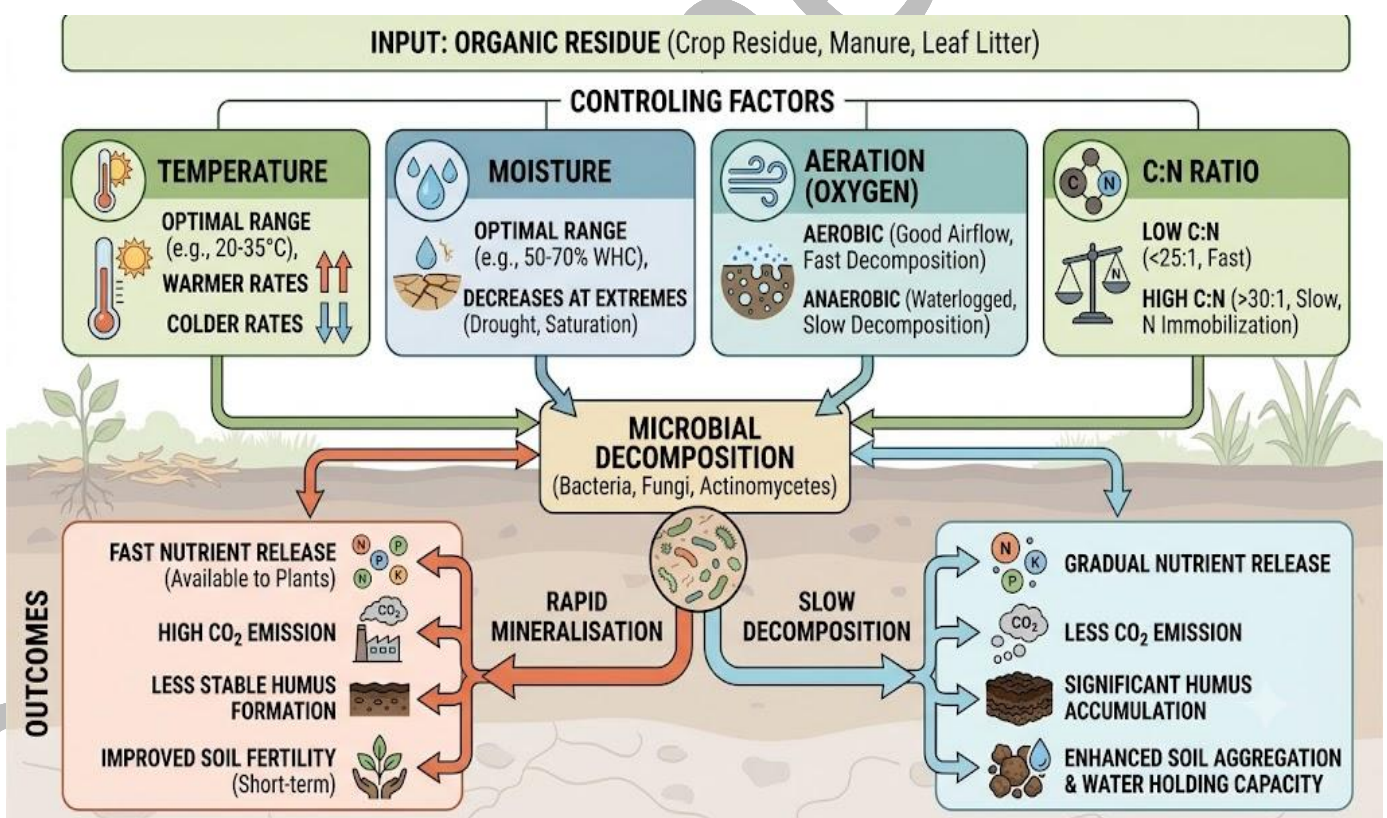

Figure 3.7: Diagram showing the decomposition process and the factors that control decomposition rate

3.3.3 Functions of organic matter in soil fertility and structure

Soil organic matter performs multiple simultaneous functions that make it the most important single indicator of long-term soil quality. Its **chemical functions** include: supplying nutrients as it mineralises (particularly nitrogen, phosphorus, and sulphur); providing a large proportion of the soil's CEC (humus has a CEC of 150 to 300 cmolc/kg, far exceeding most clay minerals); chelating micronutrients (keeping trace elements such as iron, zinc, and copper in plant-available forms rather than precipitating as insoluble hydroxides); and buffering soil pH against rapid changes.

The physical functions of organic matter include: improving soil structure through organo-mineral aggregate formation (organic matter is the primary cement binding mineral particles into stable aggregates); greatly increasing water-holding capacity (humus can absorb 80 to 90 per cent of its weight in water); reducing soil bulk density by creating pore space; reducing surface crust formation and increasing infiltration; and reducing erodibility by creating stable surface aggregates. The biological functions include: providing energy and carbon for soil microbial activity (which drives all nutrient cycling); supporting populations of soil fauna (earthworms, arthropods); and producing plant growth-promoting substances (hormones, vitamins, and enzyme activators released during decomposition). The progressive loss of soil organic matter under continuous cultivation without adequate organic inputs is the primary driver of soil degradation in Nigerian agricultural soils.

Fill in the blank: Humus has a cation exchange capacity of 150 to 300 cmolc/kg, which greatly exceeds most clay minerals, making organic matter a major contributor to the soil's nutrient-________ capacity.

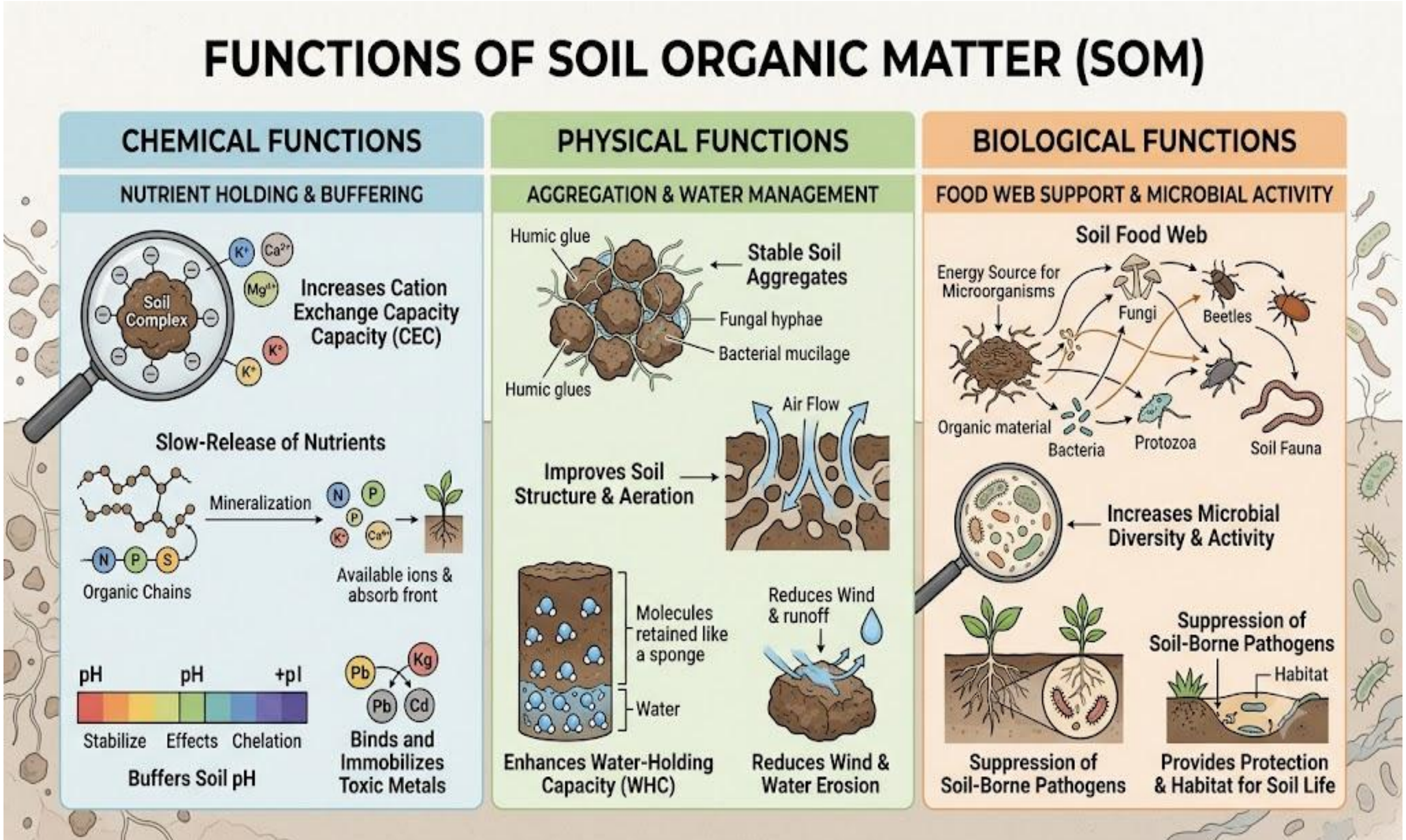

Figure 3.8: Diagram showing the three categories of organic matter functions: chemical, physical, and biological

Pilot questions 3.3

1. Define soil organic matter and name three main sources of organic inputs to agricultural soil.
2. Explain the difference between humic and non-humic organic matter fractions.
3. Explain how temperature and C:N ratio affect the rate and outcome of organic matter decomposition.
4. Distinguish between mineralisation and immobilisation of nitrogen during organic matter decomposition.
5. State three chemical functions and two physical functions of soil organic matter.

3.4 Soil Organisms

3.4.1 Categories and roles of soil organisms

Soil organisms are the biological component of the soil system, ranging in size from submicroscopic viruses and bacteria to large earthworms and burrowing mammals. They are classified by size into: **microbial biomass** (bacteria, fungi, actinomycetes, algae, and protozoa — the smallest and most numerous organisms, with the greatest collective metabolic activity); **mesofauna** (organisms 0.1 to 2 mm in size including nematodes, springtails, and mites); and **macrofauna** (organisms greater than 2 mm including earthworms, termites, beetles, ants, and small mammals). A typical Nigerian agricultural soil contains several billion bacteria, several kilometres of fungal hyphae, millions of nematodes, and thousands of earthworms per square metre of land surface.

The collective functional roles of soil organisms include: decomposition of organic residues and cycling of nutrients (predominantly by bacteria, fungi, and actinomycetes); formation and stabilisation of soil aggregates (bacteria and fungi produce polysaccharides and hyphae that bind soil particles; earthworms and termites physically mix and create stable casts); biological nitrogen fixation (by free-living Azotobacter and Clostridium and by symbiotic Rhizobium in legume root nodules); disease suppression (diverse microbial communities can suppress soil-borne pathogens); and plant growth promotion (by producing hormones and vitamins and by enhancing nutrient acquisition through mycorrhizal associations). Managing soil for high biological activity is increasingly recognised as central to sustainable soil fertility.

Fill in the blank: Soil organisms are classified by size into microbial biomass (bacteria, fungi, actinomycetes), ________ (nematodes, springtails, mites), and macrofauna (earthworms, termites, beetles).

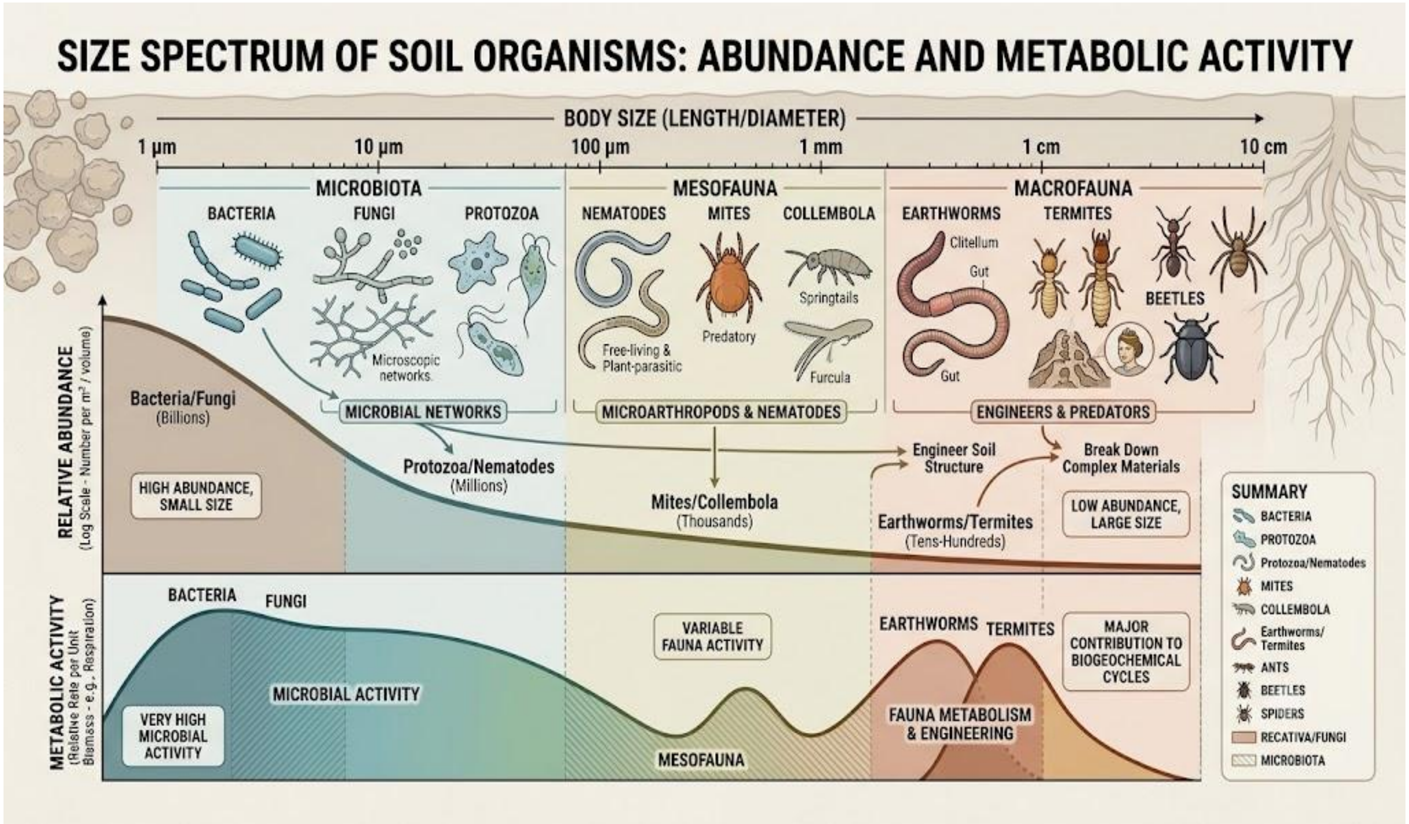

Figure 3.9: Diagram showing the size classification of soil organisms from bacteria to earthworms and their relative abundance and metabolic activity

3.4.2 Soil bacteria, fungi, and actinomycetes

Soil bacteria are the most numerous soil organisms (10^8 to 10^9 per gram of soil), responsible for the majority of organic matter decomposition in aerobic soils, nitrification (the conversion of ammonium to nitrate by Nitrosomonas and Nitrobacter), denitrification (the reduction of nitrate to nitrogen gas under anaerobic conditions by diverse bacteria), and nitrogen fixation (by free-living Azotobacter and by Rhizobium in legume nodules). Rhizobium-legume symbiosis is particularly important in Nigerian agriculture, supplying an estimated 100 to 200 kg N/ha/year to well-nodulated soybean and cowpea crops without synthetic fertiliser.

Soil fungi are less numerous than bacteria but contribute equal or greater total biomass because individual fungal cells (hyphae) are much larger. Fungi are the primary decomposers of lignin and cellulose (the structural materials of plant cell walls that resist bacterial decomposition), making them essential for the complete breakdown of crop residues. Mycorrhizal fungi (arbuscular mycorrhizal fungi, AMF) form symbiotic associations with the roots of most crop species, extending the effective root surface area by up to 100 times through their hyphal networks, dramatically improving phosphorus and zinc uptake. Actinomycetes are filamentous bacteria with a growth form resembling fungi; they produce the characteristic earthy smell of freshly turned soil (from geosmin), are important decomposers of resistant organic compounds, and are the source of most natural antibiotic compounds.

Fill in the blank: Arbuscular mycorrhizal ________ (AMF) form symbiotic associations with plant roots, extending the effective root surface area through hyphal networks and dramatically improving phosphorus and zinc uptake.

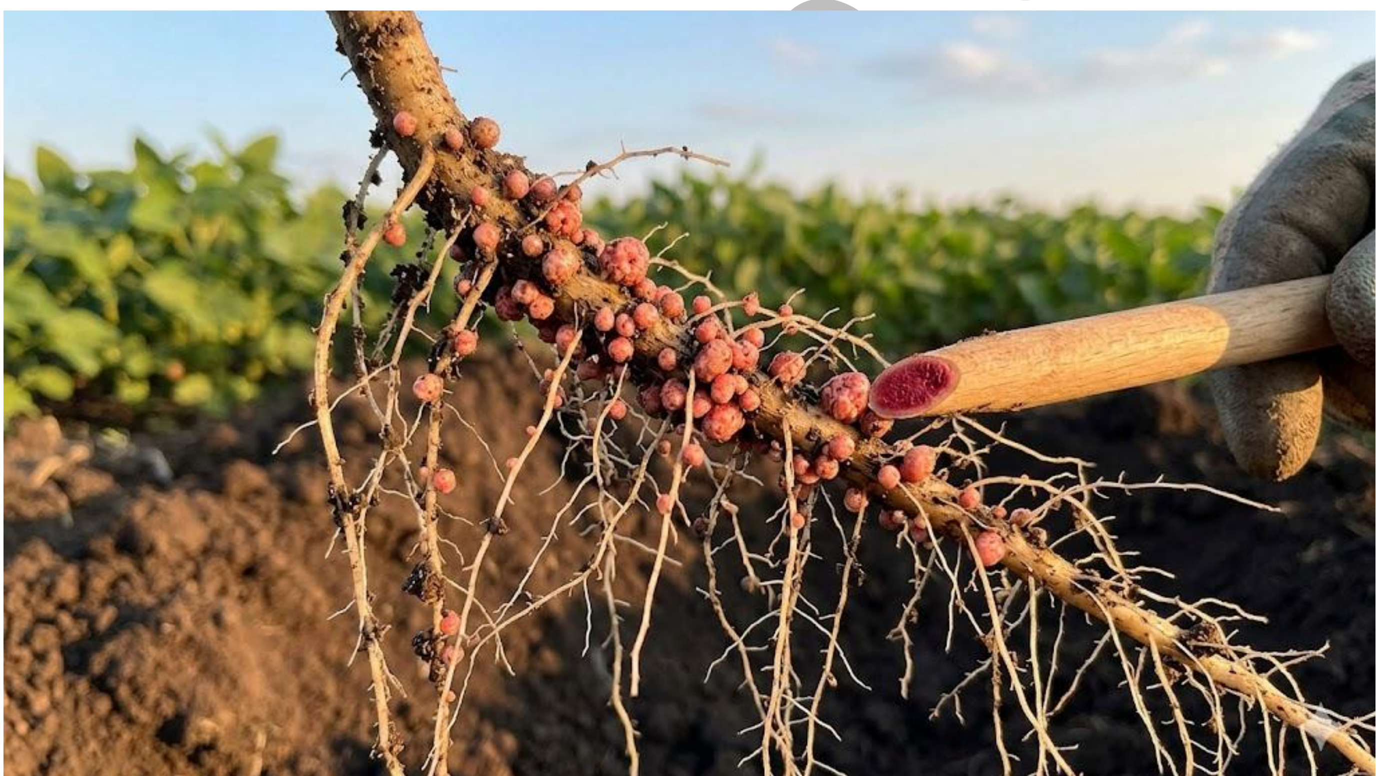

Plate 3.1: Soybean roots with Rhizobium nodules showing the symbiotic nitrogen-fixing association

3.4.3 Soil fauna and their role in soil health

Earthworms are among the most important macrofauna for soil health in non-arid environments. They consume soil along with organic matter, passing it through their gut where enzymatic digestion breaks down organic compounds and microbial activity is enhanced; the resulting casts are very stable, nutrient-rich aggregates with higher pH, CEC, and available nutrient concentrations than the surrounding soil. Earthworm burrows create large, continuous macropores (2 to 10 mm diameter) that are highly stable because they are lined with earthworm mucus; these burrows dramatically improve water infiltration and drainage in heavy-textured soils.

Termites are the dominant macrofauna in most Nigerian savanna soils and perform functions analogous to earthworms in tropical Africa, though with important differences. Termites process large volumes of soil and organic matter through their mounds, producing soil material with modified texture, chemistry, and structure. Termite mounds are substantially enriched in clay, organic matter, and nutrients relative to surrounding soil and act as fertility islands within the landscape. Termite gallery systems create deep, stable macropore networks that improve deep soil drainage. However, some termite species are serious crop pests, attacking roots, stems, and stored produce. Soil mites and springtails (mesofauna) regulate microbial populations, comminute (shred) organic residues to increase their surface area for microbial attack, and participate in nutrient cycling. Nematodes are the most abundant soil animals and include plant-parasitic species (major crop pests) as well as free-living species that graze on bacteria and fungi, releasing mineral nutrients.

Fill in the blank: Earthworm ________ are nutrient-enriched, stable aggregates with higher pH and CEC than surrounding soil, produced as earthworms digest soil and organic matter through their gut.

Plate 3.2: A termite mound in a Nigerian Guinea savanna landscape showing the soil modification activity of termites

Pilot questions 3.4

1. Classify soil organisms by size and state the main functional role of each size class.
2. Explain the role of Rhizobium bacteria in legume crop production and state the typical nitrogen contribution.
3. Describe the role of mycorrhizal fungi in improving plant nutrient uptake.
4. Describe the role of earthworms in improving soil physical properties.
5. Explain two ways in which termites influence soil properties in Nigerian savanna landscapes.

Series Summary

This Series has covered the chemical and biological dimensions of soil science that underpin soil fertility and productivity. We began with soil colloids, distinguishing inorganic colloids (clay minerals and metal oxides) from organic colloids (humus), describing the 1:1 kaolinite and 2:1 smectite clay mineral groups and their contrasting CEC values, and explaining cation exchange capacity and base saturation as the fundamental indicators of soil chemical fertility. We then examined soil pH, defining it and its logarithmic scale, explaining the factors (rainfall, leaching, organic matter decomposition, ammonium fertilisers) that cause soil acidification, and describing the effects of pH on nutrient availability with particular emphasis on aluminium toxicity and phosphorus fixation at low pH and the role of liming.

Following that, we covered soil organic matter, describing its sources and composition (humic versus non-humic fractions), the factors controlling its decomposition (temperature, moisture, aeration, C:N ratio), and the distinction between mineralisation and immobilisation; and identified its three categories of function (chemical: CEC, nutrient supply, chelation; physical: aggregation, water retention, infiltration; biological: microbial energy, fauna support). Finally, we introduced soil organisms, classifying them by size (microbial biomass, mesofauna, macrofauna), describing the specific roles of bacteria (decomposition, nitrification, nitrogen fixation), fungi (lignin decomposition, mycorrhizal phosphorus uptake), actinomycetes, earthworms, and termites in Nigerian soil contexts. By completing this Series, you should now be able to achieve all nine Series Learning Outcomes (SLO 3.1 to SLO 3.9).

Glossary of Terms

- **Active acidity:** the hydrogen ion concentration in the soil solution measured directly as pH; represents only a small fraction of the total soil acidity.
- **Aluminium toxicity:** the inhibition of plant root elongation and nutrient uptake caused by high concentrations of soluble Al3+ ions at soil pH below 5.0 to 5.5; a major crop yield constraint in strongly acid Nigerian soils.
- **Arbuscular mycorrhizal fungi (AMF):** fungi that form symbiotic associations within the root cells of most crop species, extending the effective root surface with a hyphal network that greatly improves phosphorus and zinc uptake.
- **Base saturation:** the percentage of the soil CEC occupied by basic cations (Ca2+, Mg2+, K+, Na+); high base saturation indicates a fertile, near-neutral soil; low base saturation (below 35%) indicates strongly leached, acidic soil.

- **C:N ratio:** the ratio of carbon to nitrogen in an organic material; determines the outcome of decomposition: low ratios (below 25:1) result in net nitrogen mineralisation; high ratios (above 30:1) result in temporary nitrogen immobilisation.
- **Cation exchange capacity (CEC):** the total capacity of a soil to hold exchangeable cations at a given pH; measured in centimoles of charge per kilogram (cmolc/kg); increases with clay and organic matter content and with 2:1 clay mineral proportion.
- **Chelation:** the formation of a ring-shaped complex between an organic molecule and a metal ion (such as iron, zinc, or copper) that keeps the metal in solution and plant-available rather than precipitating as an insoluble hydroxide.
- **Denitrification:** the reduction of soil nitrate to nitrogen gas (N2) or nitrous oxide (N2O) by anaerobic bacteria under waterlogged conditions; a major pathway of nitrogen loss from flooded soils.
- **Fulvic acid:** the fraction of humic substances soluble in both acid and alkali; smaller molecular weight than humic acid; highly reactive with high charge density; important in nutrient chelation and mobility.
- **Humic acid:** the fraction of humic substances soluble in alkali but precipitated by acidification; large molecular weight; contributes significantly to soil CEC and structural stability.
- **Humin:** the fraction of humic substances insoluble in both acid and alkali; the most stable and oldest fraction of soil organic matter; closely associated with the mineral fraction.
- **Immobilisation:** the temporary incorporation of mineral nutrients (particularly nitrogen and phosphorus) into microbial biomass during decomposition of high C:N ratio organic materials; reduces plant-available nutrient supply in the short term.
- **Kaolinite:** a 1:1 clay mineral with low CEC (3 to 15 cmolc/kg) and minimal swelling; the dominant clay mineral in highly weathered tropical soils including most Nigerian Alfisols, Ultisols, and Oxisols.
- **Lime requirement:** the amount of agricultural limestone needed to raise the pH of an acidic soil to a target pH; determined by buffer pH tests or titration with a liming material.

- **Mineralisation:** the release of plant-available mineral nutrients (ammonium, phosphate, sulphate) from organic compounds during microbial decomposition; the complement of immobilisation.
- **Nitrification:** the two-step oxidation of ammonium (NH_4^+) to nitrite (NO_2^-) by Nitrosomonas bacteria and then to nitrate (NO_3^-) by Nitrobacter bacteria; releases hydrogen ions, contributing to soil acidification under ammonium fertiliser applications.
- **Nitrogen fixation:** the biological conversion of atmospheric nitrogen gas (N_2) to ammonium by nitrogen-fixing organisms (free-living Azotobacter, Clostridium; symbiotic Rhizobium in legume nodules).
- **Reserve acidity:** the much larger pool of H^+ and Al^{3+} ions held on exchange sites, not measured by soil solution pH; important for calculating lime requirements.
- **Rhizobium:** a genus of soil bacteria that form symbiotic nitrogen-fixing nodules on the roots of legumes (soybean, cowpea, groundnut); can supply 100 to 200 kg N/ha/year to well-nodulated legume crops.
- **Smectite (montmorillonite):** a 2:1 expanding clay mineral with very high CEC (80 to 150 cmolc/kg) and pronounced shrink-swell behaviour; the dominant clay in Vertisols.
- **Soil organic matter (SOM):** the sum of all organic materials in the soil including living organisms, fresh residues, and decomposed humus; the most important single indicator of soil quality.
- **Soil pH:** the negative logarithm of the hydrogen ion activity in the soil solution; at pH 7 the soil is neutral, below 7 acidic, above 7 alkaline; controls nutrient availability and aluminium toxicity.
- **Variable charge:** surface charge on metal oxide and humus colloids that changes sign with pH: positive at low pH, negative at high pH; in contrast to the permanent negative charge of clay minerals like kaolinite.

Concept Check Questions [Series 3]

Objective Questions

1. Soil colloids are particles smaller than ________ mm and include clay minerals, metal oxides, and humus. (Linked to SLO 3.1)
2. ________ clay minerals have a 1:1 layer structure, low CEC, and minimal swelling; they dominate highly weathered Nigerian soils. (Linked to SLO 3.2)
3. Base saturation below ________ per cent distinguishes Ultisols from Alfisols in USDA Soil Taxonomy. (Linked to SLO 3.3)
4. At soil pH below 5.0, ________ toxicity becomes the primary chemical constraint to plant root growth and nutrient uptake. (Linked to SLO 3.5)
5. Arbuscular mycorrhizal ________ (AMF) extend the effective root surface and dramatically improve phosphorus uptake. (Linked to SLO 3.9)

Short-Answer Questions

1. Explain the difference between the CEC of kaolinite and smectite and explain the practical consequences for soil fertility. (Linked to SLO 3.2)
2. Define soil pH and explain why a change of one pH unit represents a very large change in soil acidity. (Linked to SLO 3.4)
3. Explain how the C:N ratio of an organic residue determines whether its decomposition will mineralise or immobilise nitrogen. (Linked to SLO 3.6)
4. State three chemical functions of soil organic matter. (Linked to SLO 3.7)
5. Describe two roles of earthworms in improving soil physical properties. (Linked to SLO 3.9)

Long-Answer Questions

1. Analyse soil colloids and soil reactions, describing the types of soil colloids and their charge properties, explaining the concepts of CEC and base saturation, and discussing how soil pH is determined, the factors that cause acidification in Nigerian soils, and the effects of pH on nutrient availability and plant growth. (Linked to SLOs 3.1, 3.2, 3.3, 3.4, 3.5)
2. Discuss soil organic matter as the most important indicator of soil quality, describing its sources and composition, explaining the decomposition process and the factors controlling it,

distinguishing mineralisation from immobilisation, and identifying the physical, chemical, and biological functions of organic matter in Nigerian agricultural soils. (Linked to SLOs 3.6, 3.7)

3. Evaluate the role of soil organisms in maintaining soil fertility and health, classifying organisms by size and function, explaining the specific contributions of bacteria (decomposition, nitrification, nitrogen fixation by Rhizobium), fungi (lignin decomposition, mycorrhizal nutrient uptake), and macrofauna (earthworm casts and burrows, termite mound activity) in Nigerian farming contexts. (Linked to SLOs 3.8, 3.9)

Answers to Concept Check Questions [Series 3]

Objective Questions

1. 0.001.
2. Kaolinite.
3. 35.
4. Aluminium.
5. Fungi.

Short-Answer Questions

1. Kaolinite has a CEC of only 3 to 15 cmolc/kg because its 1:1 layer structure is tightly bonded by hydrogen bonds with very limited surface charge; smectite has a CEC of 80 to 150 cmolc/kg because its 2:1 expanding layer structure has large internal surfaces with high isomorphous substitution charge; practical consequences: soils dominated by kaolinite (most Nigerian savanna and forest soils) have low nutrient-holding capacity and applied fertiliser nutrients leach rapidly with rainfall, requiring split applications and organic matter additions to improve nutrient retention; smectite-dominated soils (Vertisols) hold nutrients much more tenaciously but present severe physical management challenges.
2. Soil pH is the negative logarithm of the hydrogen ion activity (concentration) in the soil solution; pH = -log[H+]; the logarithmic nature means each unit change represents a tenfold change in H+ concentration: pH 5 has ten times more H+ than pH 6; pH 4 has one hundred times more H+ than pH 6; a seemingly small drop in pH from 6.5 to 5.5 therefore represents a

tenfold increase in acidity that dramatically changes aluminium and nutrient chemistry in the soil.

3. A low C:N ratio (below 25:1) means the residue contains sufficient nitrogen relative to carbon to meet both the nitrogen requirements of the decomposing microbial biomass and supply excess nitrogen to the soil solution as mineralised ammonium; decomposition proceeds rapidly and net nitrogen is released (mineralisation). A high C:N ratio (above 30:1) means the residue has insufficient nitrogen for the microbial biomass to decompose it while also supplying inorganic nitrogen; the microorganisms must draw on soil mineral nitrogen to decompose the high-carbon material, temporarily reducing soil mineral nitrogen availability to plants (immobilisation).
4. Any three: supplies nutrients (N, P, S, micronutrients) as it mineralises through microbial decomposition; provides a large proportion of the soil CEC through humus with 150 to 300 cmolc/kg, greatly increasing the soil's capacity to retain nutrient cations against leaching; chelates micronutrients (Fe, Zn, Cu, Mn) keeping them in plant-available soluble forms rather than precipitating as insoluble hydroxides; buffers soil pH against rapid changes by acting as a weak acid-base system that resists pH shifts.
5. Any two: earthworms consume soil and organic matter and produce casts that are very stable, nutrient-rich aggregates with higher pH, CEC, and available nutrient content than surrounding soil, improving both fertility and surface soil structure. Earthworm burrows create large (2 to 10 mm diameter), stable, continuous macropores lined with mucus that greatly improve water infiltration and drainage in clay soils, reducing surface runoff and waterlogging.

Long-Answer Questions

1. Basic response: Soil colloids: inorganic (clay minerals with permanent negative charge; metal oxides with variable charge); organic (humus with high charge density per mass). Clay minerals: 1:1 kaolinite (CEC 3 to 15, low swell, dominant in Nigeria); 2:1 smectite (CEC 80 to 150, high swell, Vertisols); illite, vermiculite. CEC: sum of exchange sites on clay and humus; increases with clay and organic matter content; measured in cmolc/kg. Base saturation: percentage of CEC occupied by Ca, Mg, K, Na; below 35% = Ultisol; raised by liming. Soil pH: -log[H+]; neutral at 7; logarithmic scale. Acidification factors: rainfall and leaching, organic acid production, ammonium fertiliser nitrification, acid parent material. pH effects: nutrients most available 6.0 to 7.5; at low pH Al toxicity, P fixation by Fe/Al, Mo deficient; at high pH Fe, Zn, Mn, B fixed by Ca.

2. Value-added response: The interaction between CEC, base saturation, and pH in Nigerian Alfisols creates a management challenge that is more complex than simply liming to raise pH. Because kaolinite-dominated Alfisols have low CEC, the base saturation can be raised quickly by liming but falls again rapidly as the added calcium is leached with subsequent rainfall events; the lime requirement is therefore not a one-time intervention but a recurring management cost. Teaching students to calculate the lime requirement correctly — accounting for the soil's low buffering capacity (low CEC) and the leaching rate of the specific rainfall regime — is the foundation for a cost-effective liming programme.
3. Basic response: SOM: sum of all organic materials; major inputs are crop residues, manures, root turnover. Composition: non-humic (cellulose, proteins, starch — rapidly decomposed); humic substances (humic acid, fulvic acid, humin — stable, high CEC). Decomposition factors: temperature (doubles per 10°C — rapid in tropics), moisture (optimal at moderate levels), aeration (aerobic faster), C:N ratio (low = mineralisation, high = immobilisation). Nigerian context: warm climate causes rapid decomposition requiring frequent large organic inputs to maintain SOM. Functions — chemical: CEC (150 to 300 cmolc/kg humus), nutrient supply (N, P, S), chelation, pH buffering; physical: aggregate formation, water retention, reduced bulk density, improved infiltration; biological: microbial energy source, fauna habitat, growth-promoting compounds.
4. Value-added response: The rapid loss of organic matter in Nigerian savanna soils under continuous tillage without organic matter additions is the most pervasive and consequential soil degradation process in the country. In the first three to five years after forest or savanna clearance, organic matter content and CEC decline dramatically, soil structure deteriorates, infiltration falls, surface crusting increases, and fertiliser responses become erratic because the physical and biological soil conditions that determine whether applied nutrients are taken up by crops rather than lost to leaching or runoff have been degraded. Reversing this decline requires a long-term commitment to organic matter management — through manure, compost, cover crops, and crop residue retention — that must be built into farming system design rather than treated as an optional add-on.
5. Basic response: Size classification: microbial biomass (bacteria, fungi, actinomycetes — highest metabolic activity, decomposition, nutrient cycling); mesofauna (nematodes, mites, springtails — regulate microbes, shred residues); macrofauna (earthworms, termites, beetles — physically mix soil, create macropores). Bacteria: decomposition, nitrification (NH_4^+ to NO_3^- by Nitrosomonas and Nitrobacter, releases H^+ acidifying soil), nitrogen fixation (Rhizobium in legume nodules — 100 to 200 kg N/ha/year for soybean, cowpea). Fungi:

lignin/cellulose decomposition; AMF extend root surface area by up to 100 times, improve P and Zn uptake. Actinomycetes: decompose resistant compounds, produce antibiotics, geosmin earthy smell. Earthworms: stable nutrient-rich casts, infiltration-improving macropores. Termites: modify soil chemistry and structure, create mound fertility islands, deep gallery drainage.

6. Value-added response: The Rhizobium-legume nitrogen fixation system represents the most cost-effective nitrogen management tool available to Nigerian smallholder farmers, yet it is widely underperforming because of two correctable factors: soil pH below 5.5 directly inhibits Rhizobium survival and nodulation efficiency, and seed inoculation with the correct Rhizobium strain is not routinely practised. A farmer who limes to pH 6.0 before soybean and inoculates seed with a virulent Rhizobium inoculant can achieve symbiotic fixation of 150 to 200 kg N/ha at zero fertiliser nitrogen cost — an economic advantage that is impossible to replicate with synthetic fertiliser at current Nigerian prices. Teaching students to diagnose poor nodulation and identify its causes (low pH, wrong Rhizobium strain, phosphorus deficiency) is one of the highest-value soil science applications in the course.

Answers to Pilot Questions [Series 3]

Part 3.1: Soil Colloids

1. Soil colloids are the finest fraction of the soil with particles smaller than 0.001 mm in at least one dimension; they have large surface area per unit mass and carry surface charges that allow them to attract and exchange ions; two main types: inorganic colloids (clay minerals and metal oxides/hydroxides of iron, aluminium, and manganese) and organic colloids (humus and partially decomposed organic materials).
2. 1:1 clay minerals have one silica tetrahedral sheet alternating with one aluminium octahedral sheet per layer; the layers are bonded tightly by hydrogen bonds giving minimal swelling, low surface area, and low CEC (kaolinite, 3 to 15 cmolc/kg). 2:1 clay minerals have two silica sheets sandwiching one aluminium sheet per layer; the interlayer space is variable allowing expansion when water enters, large surface area, and high CEC (smectite, 80 to 150 cmolc/kg).
3. Kaolinite has a much lower CEC than smectite because: kaolinite's 1:1 layer structure is tightly bonded by hydrogen bonds with very limited isomorphous substitution (replacement

of Si^{4+} by Al^{3+} or Al^{3+} by Mg^{2+}) in its crystal lattice, generating very little permanent negative charge; smectite's 2:1 structure has extensive isomorphous substitution creating a large permanent negative charge on the layer surfaces; additionally, smectite's expanding interlayer space exposes internal surfaces that are inaccessible in non-expanding kaolinite.

4. Cation exchange capacity (CEC) is the total capacity of a soil to hold exchangeable positively charged ions (cations) at a given pH, measured in cmolc/kg; it is important for soil fertility because it determines how many nutrient cations (Ca^{2+}, Mg^{2+}, K^+, NH_4^+) the soil can hold on exchange sites against leaching by percolating rainwater; soils with high CEC can retain large quantities of applied fertiliser nutrients and supply them gradually to plant roots; soils with very low CEC (sands, kaolinite-dominated tropical soils) lose applied nutrients rapidly to leaching.
5. Base saturation is the percentage of the CEC occupied by basic cations (Ca^{2+}, Mg^{2+}, K^+, Na^+) as opposed to acidic cations (H^+ and Al^{3+}); liming adds calcium carbonate ($CaCO_3$) to the soil; the calcium ions (Ca^{2+}) from the dissolving limestone occupy exchange sites, displacing H^+ and Al^{3+} from the CEC; the displaced H^+ reacts with the carbonate component to form water and CO_2; simultaneously the Al^{3+} is precipitated as insoluble $Al(OH)_3$; the result is more exchange sites occupied by Ca^{2+} (basic cation), raising base saturation and soil pH simultaneously.

Part 3.2: Soil Reactions (Soil pH)

1. Soil pH is the negative logarithm of the hydrogen ion activity in the soil solution ($-\log[H^+]$); the logarithmic nature means that each unit change on the pH scale represents a tenfold change in H^+ concentration; a soil at pH 5.0 has ten times the H^+ concentration of a soil at pH 6.0, and one hundred times the H^+ concentration of a soil at pH 7.0; this means that small numerical differences in pH represent very large differences in actual acidity, and that moving a soil from pH 5.5 to pH 6.5 by liming requires dissolving all the acid buffering capacity of the soil across a tenfold change in H^+ concentration.
2. High rainfall soils in humid Nigeria are typically strongly acidic because: heavy tropical rainfall percolates through the soil profile, dissolving and carrying away the base cations (calcium, magnesium, potassium) that were released by mineral weathering; as bases are removed from exchange sites by leaching, they are replaced by hydrogen ions (from organic acid production and carbonic acid in rainfall) and aluminium ions (released as clay minerals

are weathered); over time the exchange complex becomes dominated by H^+ and Al^{3+} rather than base cations, driving soil pH to 4.5 to 5.5 in the most intensely leached forest zone soils.

3. Ammonium-based fertilisers (urea, ammonium sulphate, ammonium nitrate) acidify the soil through the process of nitrification: nitrifying bacteria (Nitrosomonas then Nitrobacter) oxidise ammonium (NH_4^+) to nitrate (NO_3^-); this reaction releases two hydrogen ions (H^+) for every ammonium ion converted; these H^+ ions accumulate in the soil solution and on exchange sites, lowering pH; continuous application of ammonium fertilisers without liming progressively acidifies the soil, typically lowering pH by 0.1 to 0.3 units per year in well-fertilised cropping systems.
4. At low soil pH (below 5.5), phosphorus availability decreases because phosphate ions ($H_2PO_4^-$) react with abundant soluble iron and aluminium ions to form insoluble iron phosphate (strengite) and aluminium phosphate (variscite) compounds; this phosphorus fixation means that applied phosphate fertiliser is rapidly rendered unavailable; simultaneously, at pH below 5.0, Al^{3+} ions become highly soluble (the solubility of aluminium hydroxides increases sharply in strongly acid conditions) and directly toxic to plant roots, inhibiting root elongation and preventing the root from exploring the soil volume needed for water and nutrient uptake.
5. Liming adds calcium carbonate ($CaCO_3$) or calcium-magnesium carbonate (dolomite) which dissolves in soil water; Ca^{2+} and Mg^{2+} ions displace H^+ and Al^{3+} from exchange sites; H^+ reacts with carbonate to form water and CO_2; Al^{3+} is precipitated as $Al(OH)_3$; pH rises; two additional benefits beyond pH correction: supplying calcium and magnesium as plant nutrients (calcium and magnesium are macronutrients frequently deficient in strongly acidic soils); improving phosphorus availability (as pH rises from 5.0 to 6.5, iron and aluminium phosphate compounds dissolve and phosphate is released into soil solution, greatly increasing the efficiency of applied phosphate fertiliser).

Part 3.3: Soil Organic Matter

1. Soil organic matter is the sum of all organic materials in the soil including living organisms, fresh plant and animal residues, and decomposed humus; three main sources: crop residues (roots, stubble, and leaves — the largest input in most farming systems); organic manures (farmyard manure, compost, poultry manure — important supplementary inputs on small

farms); root turnover and root exudates from growing crops (substantial input often overlooked in carbon balance estimates).

2. Non-humic organic matter consists of identifiable biochemical compounds from fresh plant and animal residues: cellulose, hemicellulose, starch, proteins, fats, and sugars; these decompose relatively rapidly (weeks to months) and supply nutrients quickly but do not contribute significantly to long-term soil properties. Humic substances are large, complex, dark-coloured polymers (humic acid, fulvic acid, and humin) that are resistant to rapid decomposition; they have very high CEC, contribute strongly to soil structure through organo-mineral aggregation, and persist in the soil for decades to centuries, providing the long-term fertility and structural benefits associated with organic matter management.
3. Temperature: decomposition rate roughly doubles for every 10°C increase in temperature; in Nigeria's warm climate (25 to 35°C in the savanna zone) decomposition is rapid, consuming organic matter quickly and requiring large and frequent organic inputs to maintain SOM levels. C:N ratio: residues with low C:N ratio (below 25:1, e.g. legume leaves, manure) decompose rapidly and release net mineral nitrogen (mineralisation) because the nitrogen in the residue exceeds what the decomposer microorganisms need for their own growth; residues with high C:N ratio (above 30:1, e.g. cereal straw, dry grass) decompose slowly and temporarily immobilise soil mineral nitrogen because the microorganisms must draw on existing soil nitrogen to decompose the carbon-rich material.
4. Mineralisation is the release of plant-available inorganic nutrients (ammonium, phosphate, sulphate) from organic compounds during microbial decomposition of organic matter; it increases the plant-available nutrient supply. Immobilisation is the reverse: the temporary uptake of mineral nutrients from the soil solution into the bodies of decomposer microorganisms when they are decomposing high C:N organic materials that lack sufficient nitrogen; it reduces the plant-available nutrient supply temporarily until the microorganisms die and their own organic matter decomposes (automineralisation).
5. Three chemical: (1) supplies N, P, S, and micronutrients as it mineralises; (2) provides CEC of 150 to 300 cmolc/kg through humus, greatly increasing the soil's nutrient retention capacity; (3) chelates trace elements (Fe, Zn, Cu, Mn) keeping them in plant-available soluble forms. Two physical: (1) forms stable organo-mineral aggregates with clay particles, improving soil structure and reducing erosion; (2) greatly increases water-holding capacity because humus can absorb 80 to 90 per cent of its own weight in water.

Part 3.4: Soil Organisms

1. Size classification and roles: microbial biomass (bacteria, fungi, actinomycetes — decompose organic matter, cycle nutrients, fix nitrogen, form aggregates — highest metabolic activity per unit biomass); mesofauna (nematodes, mites, springtails, collembola — regulate microbial populations, shred residues, participate in nutrient cycling); macrofauna (earthworms, termites, beetles, ants — physically mix soil horizons, create stable macropores, process large volumes of organic matter, form nutrient-rich casts).
2. Rhizobium bacteria form symbiotic nitrogen-fixing nodules on the roots of legume crops (soybean, cowpea, groundnut, pigeon pea); within the nodules, Rhizobium converts atmospheric nitrogen gas (N_2) to ammonium (NH_3) using the enzyme nitrogenase; the ammonium is supplied to the plant for amino acid and protein synthesis in exchange for carbohydrates from the plant; well-nodulated soybean can fix 100 to 200 kg N/ha/year, greatly reducing or eliminating the need for synthetic nitrogen fertiliser and making legumes the most cost-effective nitrogen management tool for Nigerian smallholder farmers.
3. Arbuscular mycorrhizal fungi (AMF) penetrate the cortical cells of plant roots and extend an extensive network of fine hyphae (3 to 8 micrometres diameter) into the surrounding soil beyond the depletion zones that form around roots; these hyphae extend the effective root surface area by up to 100 times; phosphorus and zinc are particularly poorly mobile in soil solution because they are rapidly fixed by soil minerals and organic matter, creating very steep depletion gradients around roots; AMF hyphae bridge these depletion zones and deliver phosphorus and zinc directly to the root, dramatically improving uptake efficiency; AMF also improve water uptake and resistance to root pathogens.
4. Earthworms improve soil physical properties in two main ways: (1) casts — earthworms ingest soil and organic matter, pass them through their gut (where microbial activity is enhanced and digestion occurs), and deposit the material as casts; these casts are very stable, nutrient-rich aggregates that resist breakdown by rainfall and improve surface soil structure, aggregate stability, and nutrient availability; (2) burrows — earthworms create continuous macropores (2 to 10 mm diameter) through their burrowing activity, lined with mucus that binds the walls; these burrows conduct water very rapidly (preferential flow paths) and dramatically improve infiltration, drainage, and aeration in heavy-textured soils that would otherwise be poorly drained.
5. Any two: termites construct large mounds from subsoil material mixed with organic matter and saliva; the mound material is enriched in clay, organic matter, calcium, and other

nutrients compared with the surrounding surface soil, creating fertility islands that influence plant growth and land use patterns across the landscape. Termite gallery systems (tunnels dug deep into the soil profile in search of organic matter and water) create an extensive network of stable macropores that improve deep soil drainage and facilitate water infiltration into the subsoil, particularly important in heavy-textured savanna soils with low natural macroporosity.

References and Attributions [Series 3]

Textual References (Books and External Sources)

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- Sparks, D. L. (2003). Environmental soil chemistry (2nd ed.). Academic Press.
- Paul, E. A. (2015). Soil microbiology, ecology and biochemistry (4th ed.). Academic Press.
- Havlin, J. L., Beaton, J. D., Tisdale, S. L., & Nelson, W. L. (2013). Soil fertility and fertilizers (8th ed.). Pearson Education.
- Giller, K. E. (2001). Nitrogen fixation in tropical cropping systems (2nd ed.). CAB International.
- FAO (Food and Agriculture Organization of the United Nations). (2025). Guidelines for sustainable agriculture. FAO.

Figures, Plates, Tables, and Boxes

- Figure 3.1: Soil colloid types diagram Attribution: AI generated using prompt "Generate a two-panel diagram showing inorganic soil colloids including clay minerals and metal oxides and organic colloids including humus, with size ranges and charge types." Suggested OER search string: "soil colloids types inorganic clay minerals humus charge OER diagram".
- Table 3.1: Clay mineral comparison table Attribution: AI generated using prompt "Generate a table comparing kaolinite, smectite, illite, and vermiculite clay minerals on layer structure, CEC, swelling potential, surface area, and Nigerian occurrence." Suggested OER search string: "clay mineral types kaolinite smectite illite vermiculite CEC comparison OER table".
- Figure 3.2: CEC and base saturation diagram Attribution: AI generated using prompt "Generate a diagram of a clay or humus particle with negatively charged exchange sites occupied by nutrient cations (Ca, Mg, K) and acidic cations (H, Al), illustrating CEC and base saturation." Suggested OER search string: "cation exchange capacity CEC clay particle exchange sites nutrients diagram OER".
- Figure 3.3: Soil pH scale diagram Attribution: AI generated using prompt "Generate a pH scale from 0 to 14 showing strongly acid, moderately acid, slightly acid, neutral, and alkaline zones with typical Nigerian soil pH ranges indicated." Suggested OER search string: "soil pH scale acid neutral alkaline Nigerian soil ranges OER diagram".
- Figure 3.4: Soil acidification factors diagram Attribution: AI generated using prompt "Generate a diagram showing the factors that cause soil acidification: base cation leaching, organic acid

production, ammonium fertiliser nitrification, and acid parent material." Suggested OER search string: "soil acidification factors rainfall leaching ammonium fertiliser organic acids OER".

- Figure 3.5: Nutrient availability vs pH diagram Attribution: AI generated using prompt "Generate a bar chart showing the availability of major and micronutrients including N, P, K, Ca, Mg, Fe, Mn, B, and Zn across the soil pH range 4.0 to 9.0." Suggested OER search string: "nutrient availability soil pH diagram N P K Ca Mg Fe Mn Zn OER".
- Figure 3.6: Soil organic matter sources and fractions Attribution: AI generated using prompt "Generate a diagram showing organic matter inputs to agricultural soil and the fractions of SOM from fresh litter through decomposing material to stable humus." Suggested OER search string: "soil organic matter sources fractions fresh litter humus SOM OER diagram".
- Figure 3.7: Organic matter decomposition diagram Attribution: AI generated using prompt "Generate a diagram showing organic residue decomposition with controlling factors (temperature, moisture, aeration, C:N ratio) and outcomes of rapid mineralisation versus slow decomposition." Suggested OER search string: "organic matter decomposition factors temperature moisture CN ratio mineralisation OER".
- Figure 3.8: Organic matter functions diagram Attribution: AI generated using prompt "Generate a three-column diagram showing the chemical, physical, and biological functions of soil organic matter." Suggested OER search string: "soil organic matter functions chemical physical biological CEC aggregation OER".
- Figure 3.9: Soil organism size spectrum diagram Attribution: AI generated using prompt "Generate a size spectrum diagram of soil organisms from bacteria and fungi through nematodes and mites to earthworms and termites, showing relative abundance and metabolic activity." Suggested OER search string: "soil organisms size classification bacteria fungi earthworms termites OER diagram".
- Plate 3.1: Soybean roots with Rhizobium nodules Attribution: AI generated using prompt "Generate an image showing soybean roots with numerous pink Rhizobium nodules illustrating the symbiotic nitrogen-fixing association." Suggested OER search string: "soybean roots Rhizobium nodules symbiotic nitrogen fixation OER image".
- Plate 3.2: Termite mound in Nigerian savanna Attribution: AI generated using prompt "Generate an image of a large termite mound in a Nigerian Guinea savanna landscape illustrating the soil modification activities of termites." Suggested OER search string: "termite mound Nigeria Guinea savanna soil fauna landscape OER image".

Course code: AGE 202

Course title: Introduction to Soil Science

Course credit load: 2 Units

Series 4: Soil Water, Air, and Nutrient Cycles

- ## Part 4.1: Soil Water
    - Sub Part 4.1.1: Forms of soil water and soil water potential
    - Sub Part 4.1.2: Soil water retention and plant-available water
    - Sub Part 4.1.3: Water movement in soil
- ## Part 4.2: Soil Air and Soil Temperature
    - Sub Part 4.2.1: Composition and importance of soil air
    - Sub Part 4.2.2: Soil aeration and gas exchange
    - Sub Part 4.2.3: Soil temperature: factors, importance, and management
- ## Part 4.3: The Nitrogen Cycle in Soil
    - Sub Part 4.3.1: Nitrogen cycling processes in the soil-plant system
    - Sub Part 4.3.2: Nitrogen fixation and mineralisation
    - Sub Part 4.3.3: Nitrogen losses: leaching, denitrification, and volatilisation
- ## Part 4.4: The Phosphorus and Other Nutrient Cycles
    - Sub Part 4.4.1: The phosphorus cycle and phosphorus availability in soil
    - Sub Part 4.4.2: Potassium, calcium, magnesium, and sulphur cycles
    - Sub Part 4.4.3: Micronutrient cycles and nutrient management principles

Introduction

Water, air, and nutrients are the three immediate inputs that the soil delivers to plants. The availability of each is controlled by the physical and chemical properties of the soil, and the interactions between them are constant: water occupies pore space at the expense of air; nutrients move with water; biological processes that cycle nutrients are driven by the availability of water and oxygen. Understanding how these systems work — individually and in combination — is fundamental to diagnosing the cause of poor crop performance and designing management strategies to correct it.

The aim of this Series is to introduce you to the forms and movement of soil water, the importance of soil air and temperature, the nitrogen cycle in the soil-plant system, and the cycles of phosphorus, potassium, and other major and micronutrients in the soil.

We shall commence this Series by examining soil water and its availability to plants. Next, we will study soil air and soil temperature. Following that, we will cover the nitrogen cycle including fixation, mineralisation, and the main pathways of nitrogen loss. Finally, we will wrap up with the phosphorus cycle, the secondary macronutrients, and the principles of integrated nutrient management.

Series Learning Outcomes

Upon completing this Series, you should be able to:

- **SLO 4.1** describe the forms of soil water, define soil water potential, and explain how it determines water availability to plants (Linked to Part 4.1),
- **SLO 4.2** define field capacity and permanent wilting point and calculate plant-available water (Linked to Part 4.1),
- **SLO 4.3** explain the processes of water infiltration, percolation, and capillary rise in soil (Linked to Part 4.1),
- **SLO 4.4** describe the composition and importance of soil air and explain how soil aeration is maintained (Linked to Part 4.2),

- **SLO 4.5** explain the factors controlling soil temperature and describe its effects on plant growth and soil biological activity (Linked to Part 4.2),
- **SLO 4.6** describe the major processes of the nitrogen cycle including fixation, mineralisation, nitrification, and denitrification (Linked to Part 4.3),
- **SLO 4.7** explain the main pathways of nitrogen loss from soil and describe management practices to minimise these losses (Linked to Part 4.3),
- **SLO 4.8** describe the phosphorus cycle and explain why phosphorus availability is frequently limiting in tropical soils (Linked to Part 4.4), and
- **SLO 4.9** describe the cycles of potassium, calcium, magnesium, sulphur, and micronutrients and explain the principles of integrated nutrient management (Linked to Part 4.4).

4.1 Soil Water

4.1.1 Forms of soil water and soil water potential

Soil water exists in three forms based on how tightly it is held by the soil. **Gravitational water** is water held in the large macropores (above 0.05 mm diameter); it drains freely under gravity after rainfall ceases, typically within one to three days, and is generally unavailable to plants before it drains. **Capillary water** is held in the fine pores (0.0002 to 0.05 mm) by surface tension forces; it is the primary source of plant-available water and is retained against gravity. **Hygroscopic water** is held as a thin film on soil particle surfaces by strong adsorption forces; it is essentially unavailable to plants.

Soil water potential (measured in kilopascals, kPa, or bars) describes the energy status of water in the soil relative to pure free water; it is the force that the plant must overcome to extract water. At saturation, water potential is near zero. As the soil dries, water potential becomes increasingly negative (more negative = harder for plants to extract water). Field capacity (the water content after free drainage ceases) corresponds to a water potential of approximately -10 to -33 kPa. The permanent wilting point (the water content at which plants can no longer extract water and wilt irreversibly) corresponds to a potential of approximately -1,500 kPa. Plant-available water is the difference in water content between field capacity and the permanent wilting point.

Fill in the blank: Soil water ________ describes the energy status of water in the soil; at field capacity it is approximately -10 to -33 kPa, and at the permanent wilting point approximately -1,500 kPa.

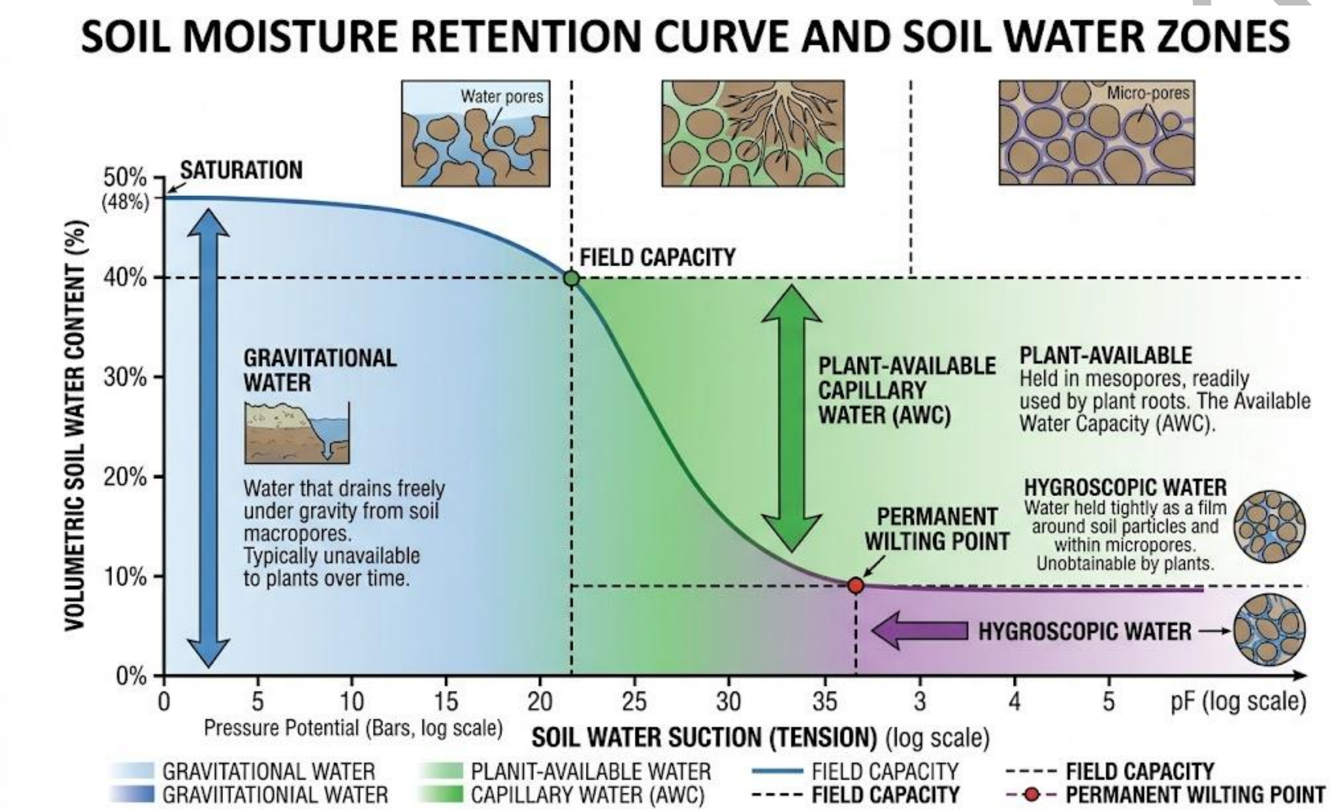

Figure 4.1: Diagram showing the three forms of soil water and their corresponding water potential ranges and plant availability

4.1.2 Soil water retention and plant-available water

Field capacity (FC) is the volumetric water content of a soil after excess gravitational water has drained away, typically one to three days after saturation; it represents the upper limit of plant-available water storage. **Permanent wilting point (PWP)** is the water content at which water remaining in the soil is held so tightly that plants can no longer extract it at a rate sufficient to maintain turgor, and wilt irreversibly; it represents the lower limit of plant-available water. **Plant-available water (PAW)** = FC - PWP, expressed as a volumetric percentage or as millimetres of water per metre of soil depth.

Soil texture strongly influences both FC and PWP: clay soils hold much more total water than sandy soils at both FC and PWP, but the plant-available water content is similar or only moderately higher because clay soils also hold more water at the PWP (water held tightly by the large clay surface area). Sandy soils have low total water storage but a high proportion of that water is available because the large pores drain and fill more freely. A sandy loam soil might hold 60 to 100 mm of plant-available water per metre of soil depth, a loam 120 to 160 mm, and a clay loam 100 to 140 mm. Organic matter significantly increases plant-available water by increasing the total porosity and the proportion of fine pores that retain water at potentials accessible to roots.

Fill in the blank: Plant-available water is calculated as the difference between ________ capacity and the permanent wilting point, expressed as volumetric percentage or mm of water per metre of soil depth.

Soil Type	**Field Capacity (% by volume)**	**Permanent Wilting Point (% by volume)**	**Plant-Available Water (% by volume)**
Sandy soil	~10	~5	~5
Sandy loam	~20	~10	~10
Loam soil	~30	~15	~15
Clay loam	~35	~20	~15
Clay soil	~40	~25	~15

Table 4.1: Typical field capacity, permanent wilting point, and plant-available water values for different soil textural classes

4.1.3 Water movement in soil

Infiltration is the entry of water into the soil from the surface. The infiltration rate (mm per hour) is highest in dry, well-structured soils with abundant macropores and decreases rapidly as pores fill and surface swelling and sealing occur. Sandy soils have high but relatively constant infiltration rates; clay soils have high initial rates (when dry and cracked) that fall sharply as they wet and swell. Surface crusts in structureless soils drastically reduce infiltration and cause surface runoff and erosion even at moderate rainfall intensities.

Percolation is the downward movement of water through already saturated or near-saturated soil by gravity. It is the primary mechanism of deep drainage, leaching of soluble nutrients, and recharge of groundwater aquifers. In sandy soils, percolation is rapid; in clay soils, slow. Capillary rise is the upward movement of water from a water table or saturated layer through small soil pores, driven by the surface tension forces that created capillary water retention; it can supply water to plant roots from a shallow water table (within 1 to 2 m depth) and can also transport dissolved salts upward, causing surface salinisation in irrigated areas with poor drainage. Preferential flow through macropores (earthworm channels, root channels, cracks) can carry water and solutes rapidly to depth, bypassing the fine pore matrix and reducing both plant water availability and contaminant removal.

Fill in the blank: ________ rise is the upward movement of water through fine soil pores from a water table or saturated layer driven by surface tension, which can supply plant roots but may also cause surface salinisation in poorly drained irrigated soils.

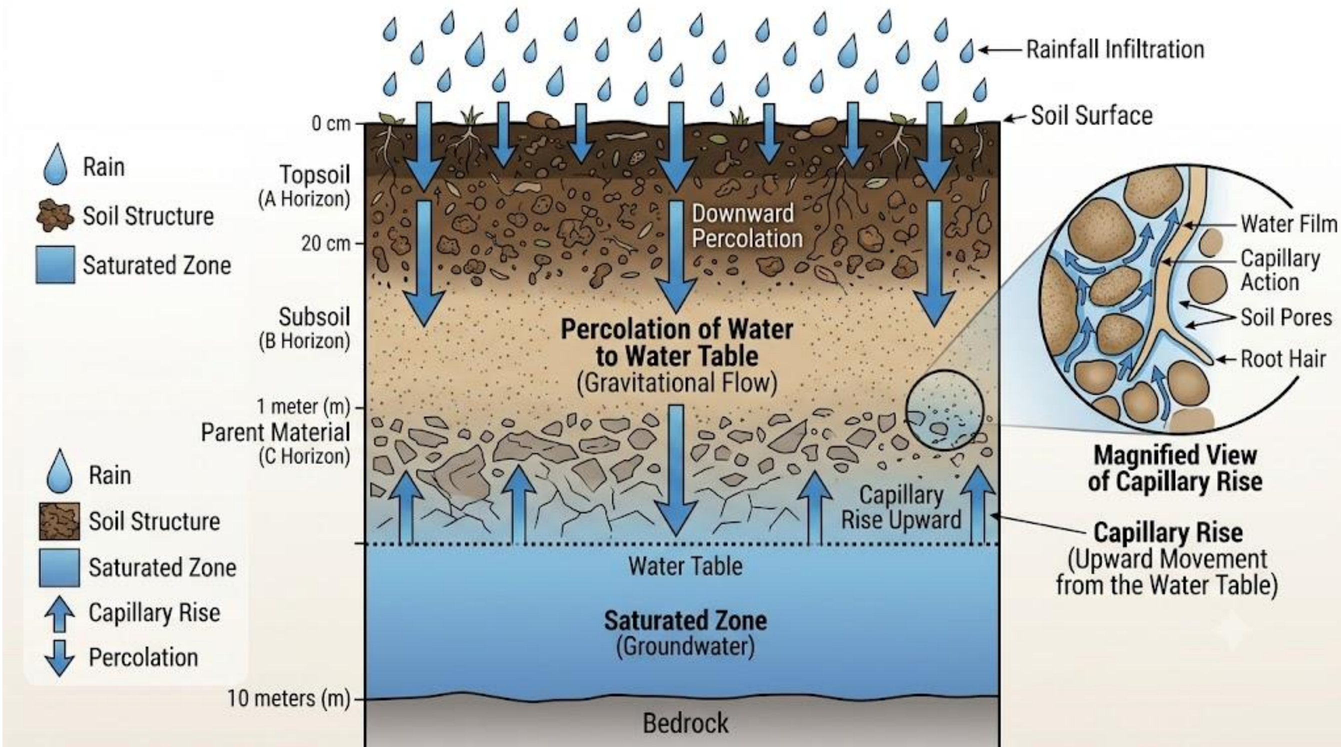

Figure 4.2: Diagram showing the three types of water movement in soil: infiltration, percolation, and capillary rise

Pilot questions 4.1

6. Define gravitational water, capillary water, and hygroscopic water and state which is the primary source of plant water.
7. Define soil water potential and explain why it becomes more negative as the soil dries.
8. Define field capacity and permanent wilting point and explain how plant-available water is calculated.
9. Explain why sandy soils have lower plant-available water storage than loam soils despite draining more freely.
10. Explain what surface crusting is and how it affects water infiltration.

4.2 Soil Air and Soil Temperature

4.2.1 Composition and importance of soil air

Soil air occupies the pore spaces not filled by water. Its composition differs from atmospheric air in several important ways: soil air typically has a lower oxygen content (15 to 20 per cent versus 21 per cent in the atmosphere), much higher carbon dioxide content (0.3 to 5 per cent versus 0.04 per cent in the atmosphere), higher water vapour content (near saturation at most times), and may contain traces of methane, hydrogen sulphide, and nitrous oxide produced by anaerobic microbial activity. The elevated CO2 and reduced O2 in soil air reflect the continuous consumption of oxygen and production of CO2 by root respiration and microbial decomposition of organic matter.

Adequate oxygen in the soil air is essential for root respiration: plant roots require oxygen to sustain the aerobic respiration that provides the energy for active nutrient uptake. When oxygen concentration in the soil falls below approximately 10 per cent, root respiration is impaired, nutrient uptake decreases, and anaerobic fermentation products (ethanol, acetaldehyde) accumulate and damage root cells. In waterlogged soils where oxygen is depleted, iron and manganese are reduced to soluble forms that may reach toxic concentrations; nitrogen is lost through denitrification; and hydrogen sulphide (toxic to roots) is produced from sulphate reduction. Only specialised crops (rice, aquatic vegetables) are adapted to survive sustained anaerobic soil conditions.

Fill in the blank: Soil air has a higher ________ dioxide content than atmospheric air because root respiration and microbial decomposition continuously consume oxygen and release CO2 in the soil pore space.

Gas Component	Atmospheric Air (%)	Soil Air (%)	Significance
Oxygen (O_2)	~21	~10–15	Lower in soil due to microbial respiration; critical for root and microbial activity

Carbon dioxide (CO_2)	~0.03–0.04	~0.3–3.0	Much higher in soil; product of root and microbial respiration; influences soil pH and nutrient solubility
Nitrogen (N_2)	~78	~78	Similar to atmosphere; inert but important for soil aeration balance
Water vapour	Variable (0–4)	Higher and more variable	Strongly influenced by soil moisture; affects microbial activity and plant water relations

Table 4.2: Comparison of soil air composition with atmospheric air for oxygen, carbon dioxide, nitrogen, and water vapour

4.2.2 Soil aeration and gas exchange

Soil aeration is the exchange of gases between the soil and the atmosphere, replenishing oxygen consumed by roots and microorganisms and removing excess CO2. Gas exchange occurs by two mechanisms: **diffusion** (the slow movement of gas molecules down their concentration gradient — the primary mechanism under non-saturated conditions; O2 diffuses inward because it is depleted by respiration; CO2 diffuses outward because it accumulates); and **mass flow** (bulk movement of air driven by temperature and pressure differences between the soil and atmosphere, and by rainfall events that displace air from pores as water enters).

Good aeration depends on the presence of air-filled pores and on rapid diffusion rates through those pores. Compaction (from heavy traffic or tillage on wet soil) destroys macropores and dramatically reduces aeration. Waterlogging replaces all air-filled pores with water, through which oxygen diffuses approximately 10,000 times more slowly than through air, leading rapidly to anaerobic conditions. Sandy soils with large pores are generally well aerated; clay soils with small pores and high water retention are prone to poor aeration, especially when wet. Management practices that improve aeration include: drainage installation, subsoiling to break compacted pans, avoiding tillage on wet soil, adding organic matter to improve soil structure and macroporosity.

Fill in the blank: Gas exchange in soil occurs primarily by ________, the slow movement of gas molecules down their concentration gradient, which replenishes O2 consumed by respiration and removes CO2 from the root zone.

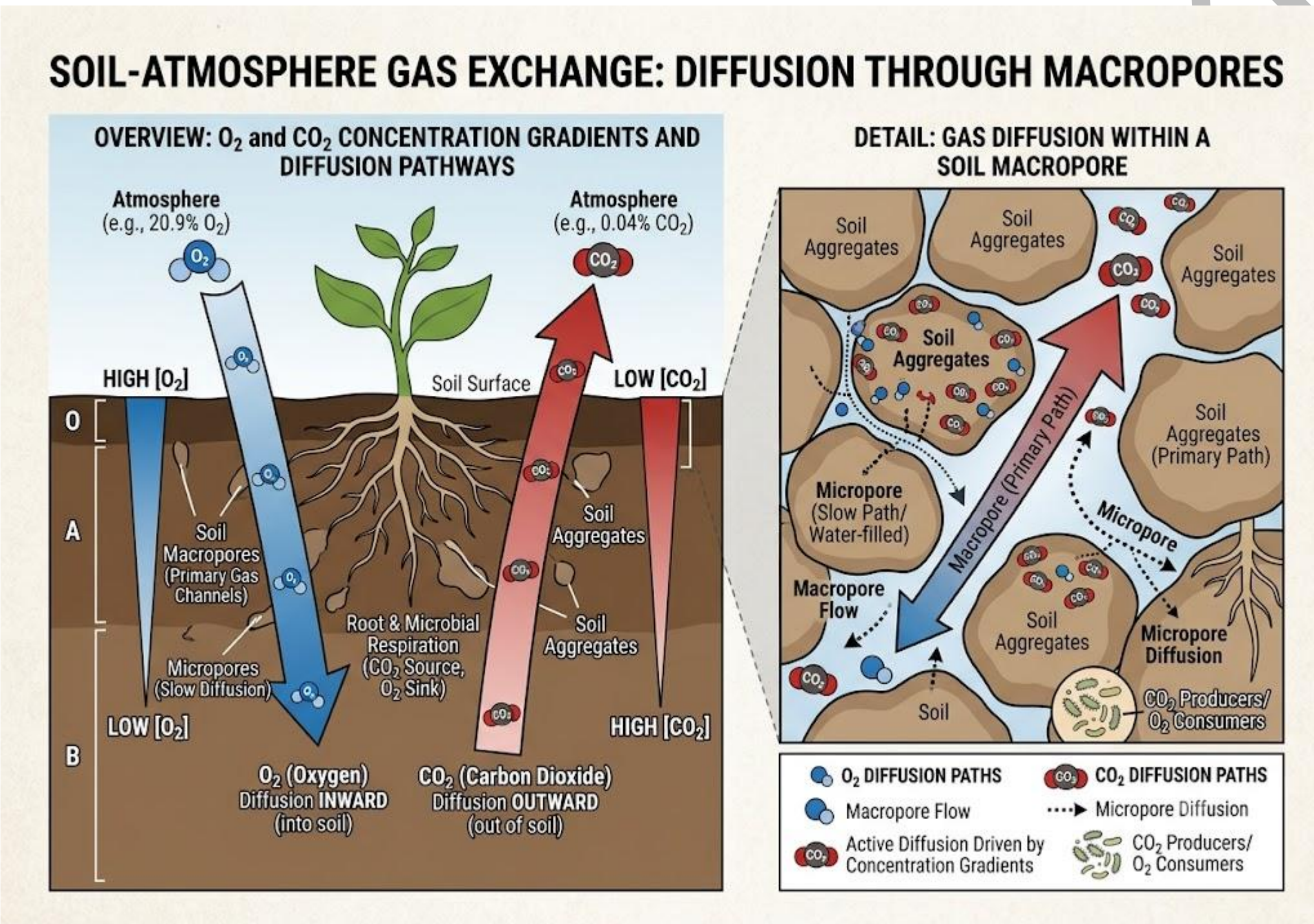

Figure 4.3: Diagram showing gas exchange between soil and atmosphere by diffusion and mass flow through soil macropores

4.2.3 Soil temperature: factors, importance, and management

Soil temperature is controlled by the balance between energy inputs (solar radiation absorbed at the soil surface) and energy losses (radiation back to the atmosphere, evaporation of water from the surface, and conduction of heat into the deeper soil). Factors that influence soil temperature include: soil colour (dark soils absorb more solar radiation than light soils), soil water content (wet soils have higher heat capacity and warm more slowly than dry soils), surface cover (bare soil heats rapidly; vegetation cover or mulch moderates temperature extremes), slope and aspect (south-facing slopes in the northern hemisphere receive more radiation), and depth (temperature fluctuations are greatest at the surface and diminish with depth; a diurnal temperature wave penetrates to approximately 50 cm depth in most soils).

Soil temperature profoundly influences crop production and soil processes. Seed germination requires minimum threshold temperatures (maize requires soil temperatures above 10°C; cowpea above 15°C); germination rates increase with temperature up to an optimum (25 to 30°C for most tropical crops). Chemical weathering rates, organic matter decomposition, and nutrient mineralisation rates all increase with temperature. In Nigeria's humid tropics, high soil temperatures (30 to 40°C at the surface in the dry season) can limit germination, kill seedlings, and desiccate roots near the surface. Management practices to moderate soil temperature include mulching (reduces both maximum daytime temperature and minimum night temperature, keeps soil cooler in summer and warmer at night), irrigation, and cover cropping.

Fill in the blank: ________ reduces maximum daytime soil temperature and moderates minimum night temperature, protects seeds from extreme surface heat, and keeps the soil cooler and more biologically active in the dry season.

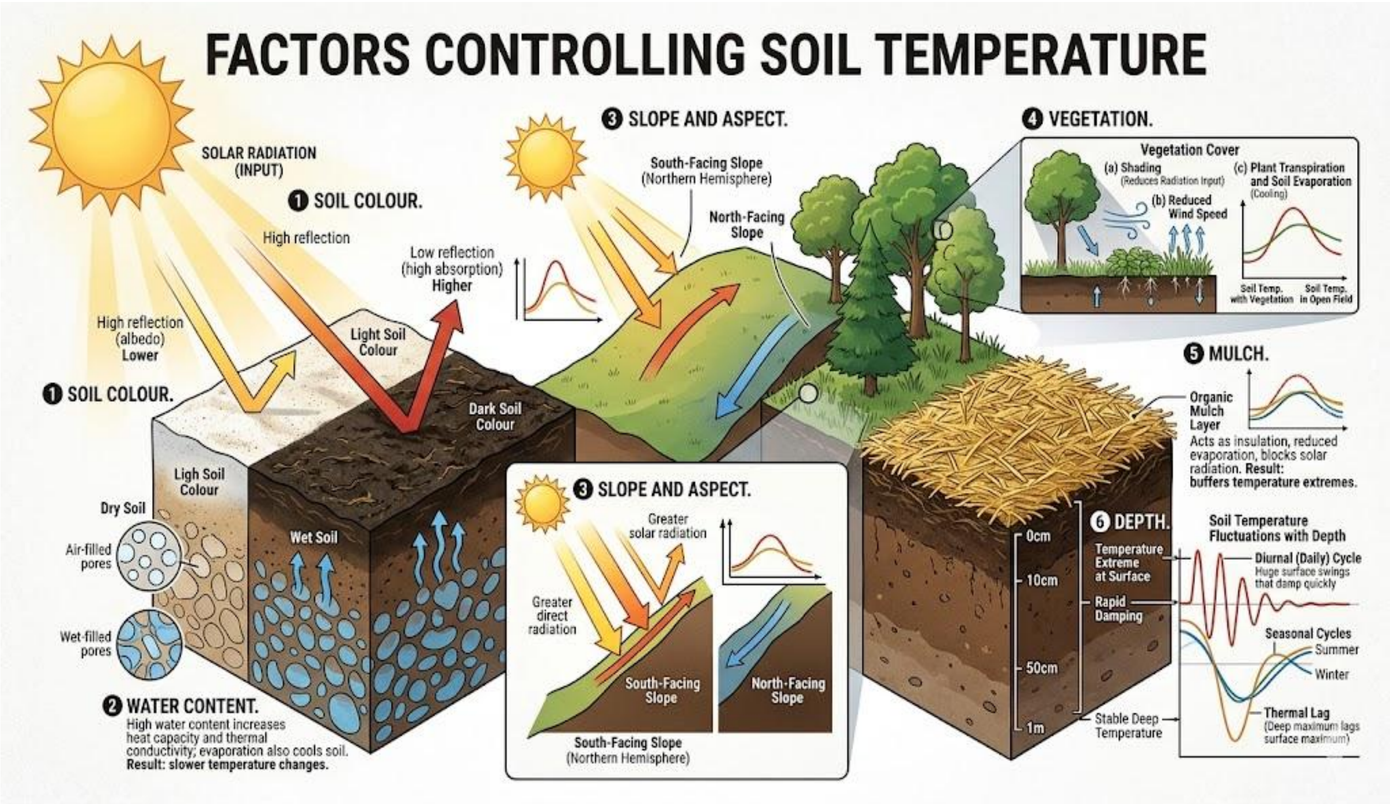

Figure 4.4: Diagram showing the factors controlling soil temperature and their relative effects on soil warming and cooling

Pilot questions 4.2

1. State three ways in which the composition of soil air differs from atmospheric air.
2. Explain why oxygen is essential for plant root function and what happens when soil oxygen falls below 10 per cent.
3. Define soil aeration and explain how it occurs by diffusion.
4. Explain how compaction reduces soil aeration and describe one management practice to restore aeration.
5. Explain why mulching is an effective management practice for moderating soil temperature in Nigerian dry season conditions.

4.3 The Nitrogen Cycle in Soil

4.3.1 Nitrogen cycling processes in the soil-plant system

The nitrogen cycle describes the continuous transformation of nitrogen between its organic and inorganic forms in the soil-plant-atmosphere system. The major processes are: **nitrogen fixation** (conversion of atmospheric N2 to ammonium by biological organisms), **mineralisation** (release of ammonium from organic nitrogen during decomposition), **nitrification** (conversion of ammonium to nitrate by bacteria), **plant uptake** (absorption of nitrate and ammonium by roots), **immobilisation** (incorporation of mineral nitrogen into microbial biomass), and **nitrogen losses** (denitrification, leaching, volatilisation, and erosion).

Nitrogen is the nutrient most frequently limiting crop production in Nigerian soils, both because soils have inherently limited nitrogen-supplying capacity and because nitrogen is easily lost from the soil system through leaching, denitrification, and volatilisation. The soil nitrogen cycle is therefore central to understanding and improving nitrogen use efficiency in Nigerian agriculture. The soil organic nitrogen pool (held in humus and other organic forms) is the largest nitrogen reservoir in most agricultural soils and serves as a slow-release source of nitrogen through mineralisation; the inorganic nitrogen pool (ammonium and nitrate in soil solution) is small and highly dynamic, turning over rapidly through uptake, immobilisation, and loss processes.

Fill in the blank: The largest nitrogen reservoir in most agricultural soils is the soil ________ nitrogen pool, held in humus and other organic forms, which releases nitrogen slowly through mineralisation.

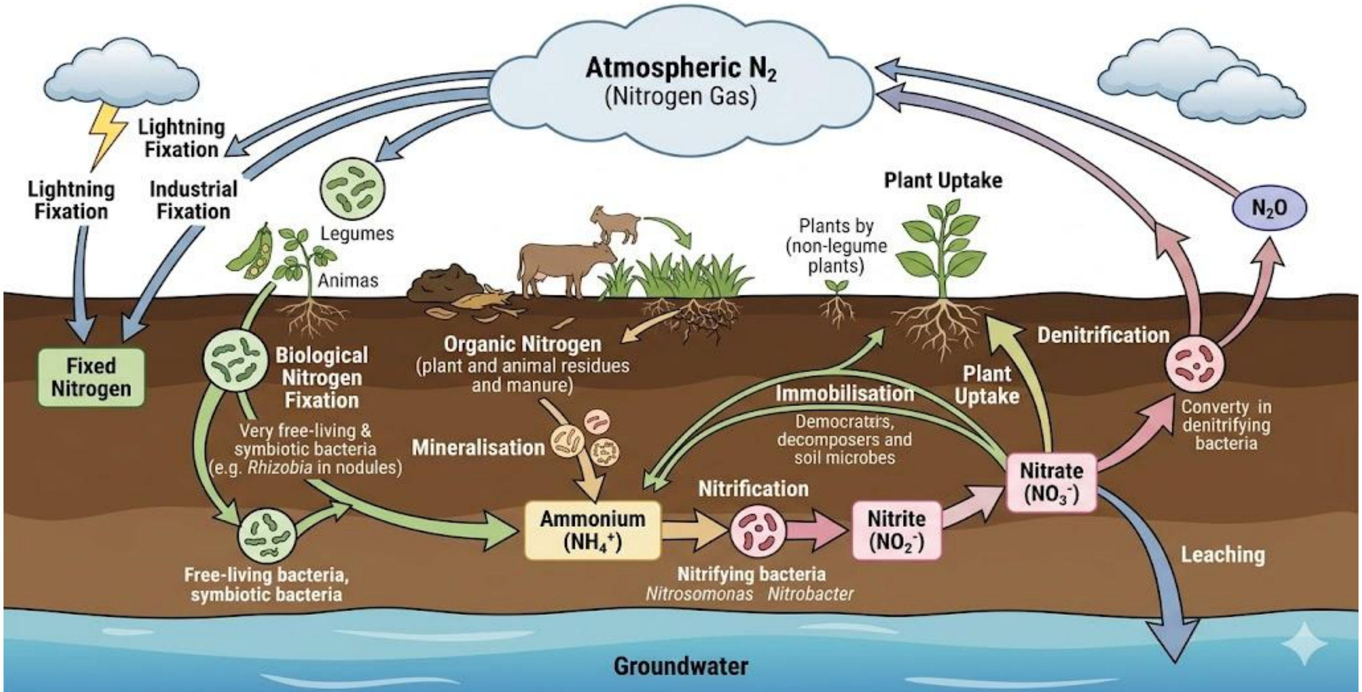

Figure 4.5: Diagram of the nitrogen cycle showing all major transformation processes and fluxes in the soil-plant-atmosphere system

4.3.2 Nitrogen fixation and mineralisation

Biological nitrogen fixation (BNF) converts atmospheric nitrogen gas (N2) to ammonium using the enzyme nitrogenase, which requires anaerobic conditions at the enzyme site and large amounts of ATP (energy). The most agronomically important BNF is symbiotic fixation by Rhizobium bacteria in the root nodules of leguminous crops: well-nodulated soybean can fix 100 to 200 kg N/ha per crop; cowpea 30 to 100 kg N/ha; groundnut 50 to 100 kg N/ha. This nitrogen enters the soil nitrogen cycle when the nodules and crop residues decompose after harvest, contributing to the nitrogen supply for subsequent crops in a rotation.

Nitrogen mineralisation is the release of inorganic ammonium from organic nitrogen compounds by soil microorganisms during the decomposition of organic matter. It follows the same pathway as organic matter decomposition: fresh organic residues with low C:N ratios mineralise rapidly (releasing net ammonium within days to weeks), while high C:N materials immobilise nitrogen initially and mineralise slowly over months. In a well-managed soil with moderate organic matter content, mineralisation may supply 20 to 80 kg N/ha per season, reducing (but rarely eliminating) the need for synthetic nitrogen fertiliser. The rate of mineralisation is strongly temperature-dependent: mineralisation in Nigerian savanna soils increases rapidly at the start of the rainy season when soils warm and wet, often producing a flush of mineral nitrogen that coincides with early crop demand.

Fill in the blank: Nitrogen ________ releases plant-available ammonium from organic nitrogen in soil organic matter and crop residues; the rate depends on temperature, moisture, and the C:N ratio of the substrate.

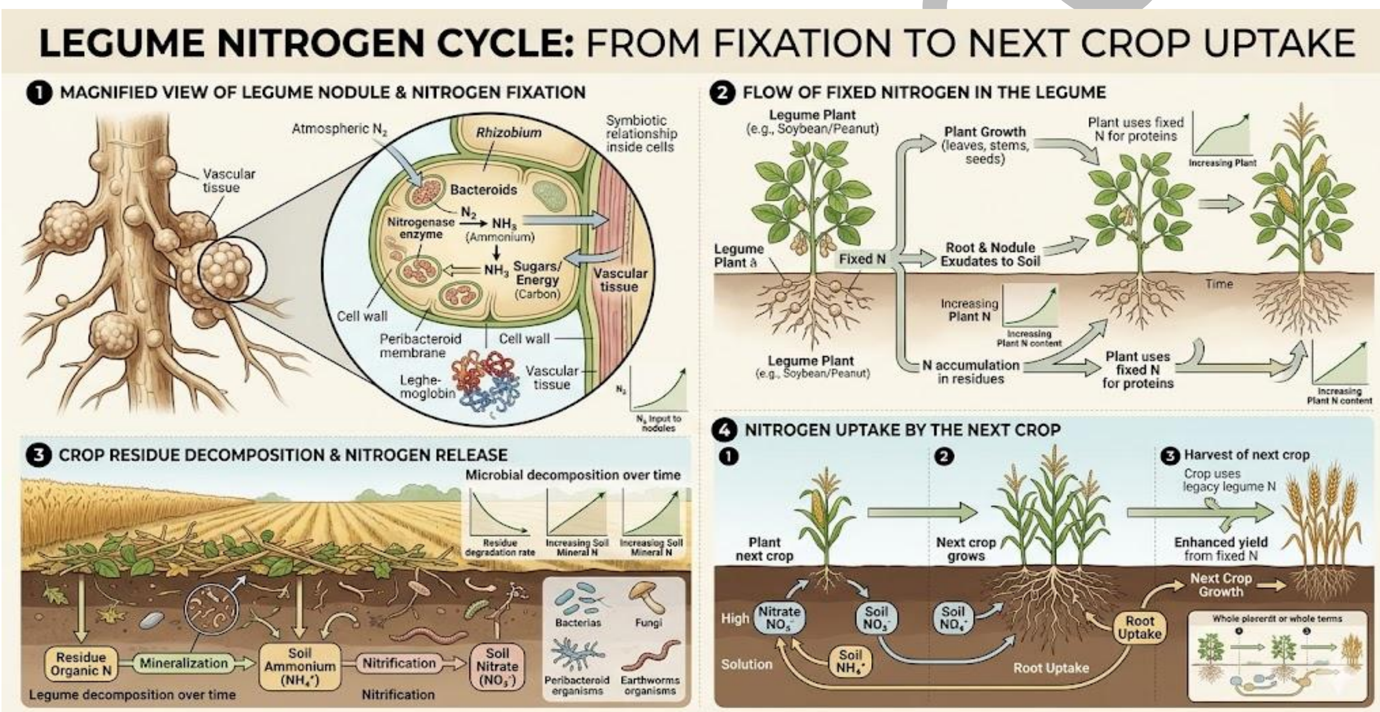

Figure 4.6: Diagram showing biological nitrogen fixation by Rhizobium in legume nodules and the fate of fixed nitrogen in the soil-plant system

4.3.3 Nitrogen losses: leaching, denitrification, and volatilisation

Nitrate leaching is the movement of nitrate ions (NO3-) downward through the soil profile with percolating water, carrying them below the root zone and into groundwater. Nitrate is particularly vulnerable to leaching because it carries a negative charge and is therefore not held on the negatively charged exchange sites of clay and humus (unlike ammonium, which is positively charged and held by CEC); it moves freely in the soil solution. Leaching losses are highest in sandy soils with low CEC, in high-rainfall periods, and after applications of nitrate fertilisers or after nitrification of ammonium.

Denitrification is the reduction of nitrate to nitrogen gas (N_2) and nitrous oxide (N_2O) by anaerobic bacteria (Pseudomonas, Paracoccus) under waterlogged or near-saturated conditions with abundant organic carbon. N_2O is a potent greenhouse gas (approximately 300 times more warming than CO_2 over 100 years); denitrification is therefore both a nitrogen loss pathway and a climate impact. Ammonia volatilisation is the loss of nitrogen as ammonia gas (NH_3) from the soil surface when urea or ammonium-containing fertilisers are broadcast on the surface without incorporation: urea is hydrolysed to ammonium carbonate by the enzyme urease; the ammonium converts to gaseous NH_3 at high pH (above 7.0) or when surface temperature is high. Incorporation of urea fertiliser into the soil, acidic soil conditions, and mulching that keeps the surface cool and moist all reduce volatilisation losses.

Fill in the blank: Nitrate is particularly vulnerable to ________ because its negative charge prevents it from being held on the negatively charged exchange sites of clay and humus, so it moves freely with soil water.

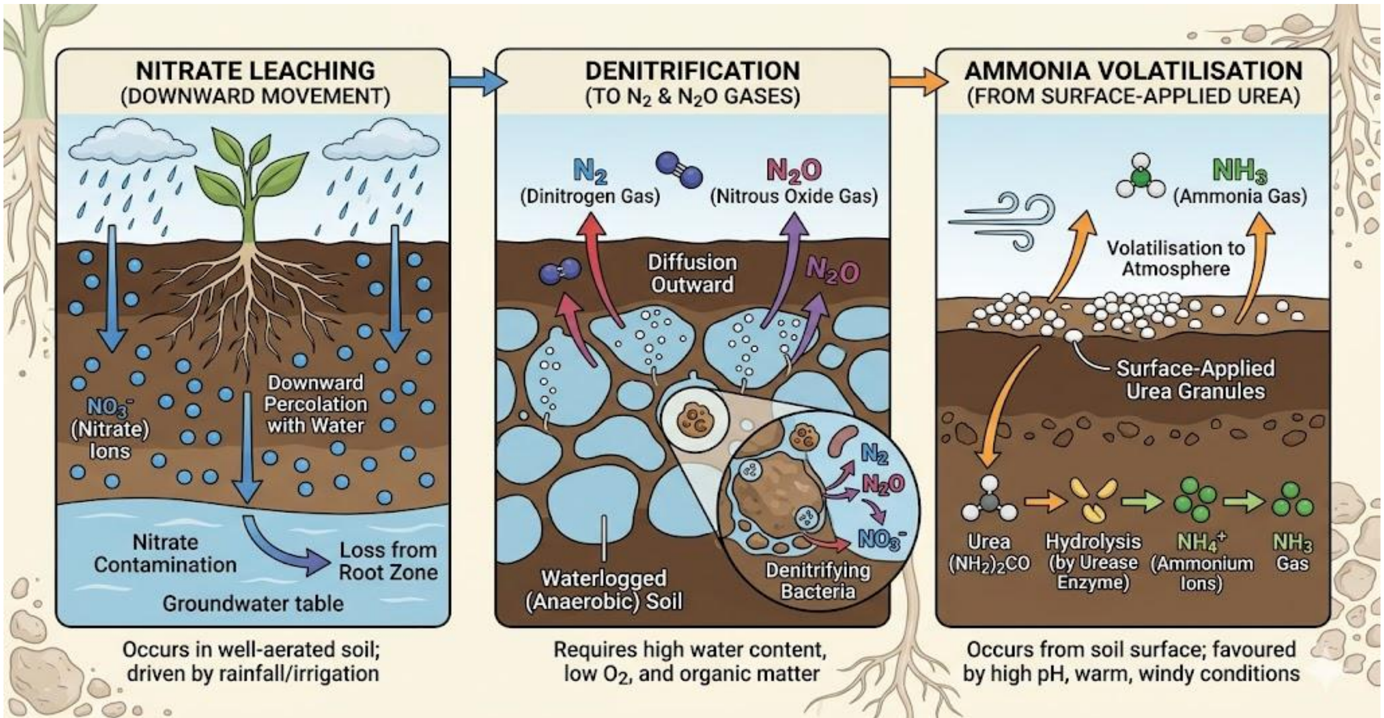

Figure 4.7: Diagram showing the three main nitrogen loss pathways from soil: nitrate leaching, denitrification, and ammonia volatilisation

Pilot questions 4.3

1. Name the six major processes of the nitrogen cycle in the correct sequence from fixation to loss.
2. Explain the difference between symbiotic and free-living biological nitrogen fixation and give one example of each.
3. Define nitrogen mineralisation and explain the factors that control its rate.
4. Explain why nitrate is more susceptible to leaching than ammonium.
5. Describe two management practices that reduce nitrogen losses from soil.

4.4 The Phosphorus and Other Nutrient Cycles

4.4.1 The phosphorus cycle and phosphorus availability in soil

The phosphorus cycle differs fundamentally from the nitrogen cycle in that there is no atmospheric reservoir: phosphorus cycles only between soil minerals, organic matter, soil solution, and plants. The soil phosphorus pool exists in three forms: **soil solution phosphorus** (orthophosphate ions H2PO4- and HPO42- dissolved in soil water — the only form directly absorbed by roots, and the smallest and most dynamic pool); **labile phosphorus** (phosphorus loosely adsorbed on soil particle surfaces and in rapid equilibrium with soil solution); and **non-labile phosphorus** (phosphorus strongly fixed to iron and aluminium oxides and clay minerals, or locked in primary mineral apatite — the largest but least available pool).

In highly weathered tropical soils (Oxisols, Ultisols, and many Alfisols in Nigeria), phosphorus fixation by iron and aluminium oxides is the primary constraint on phosphorus availability: applied phosphate fertiliser reacts rapidly with Fe and Al to form insoluble iron phosphate and aluminium phosphate compounds, reducing the efficiency of fertiliser phosphorus to as low as 10 to 15 per cent. Management strategies to improve phosphorus availability include: applying phosphate in bands (concentrating it in a zone where it is less exposed to fixation); combining phosphate with organic matter additions (organic acids from decomposition compete with phosphate for fixation sites, reducing fixation); using rock phosphate (direct application of partially soluble calcium phosphate mineral, effective in strongly acidic soils where it dissolves slowly); raising soil pH by liming (reduces Fe and Al solubility and fixation); and using mycorrhizal fungi (which access phosphorus from a much larger soil volume than roots alone).

Fill in the blank: In highly weathered tropical soils, ________ fixation by iron and aluminium oxides is the primary constraint on phosphorus availability, reducing the efficiency of applied phosphate fertiliser to as low as 10 to 15 per cent.

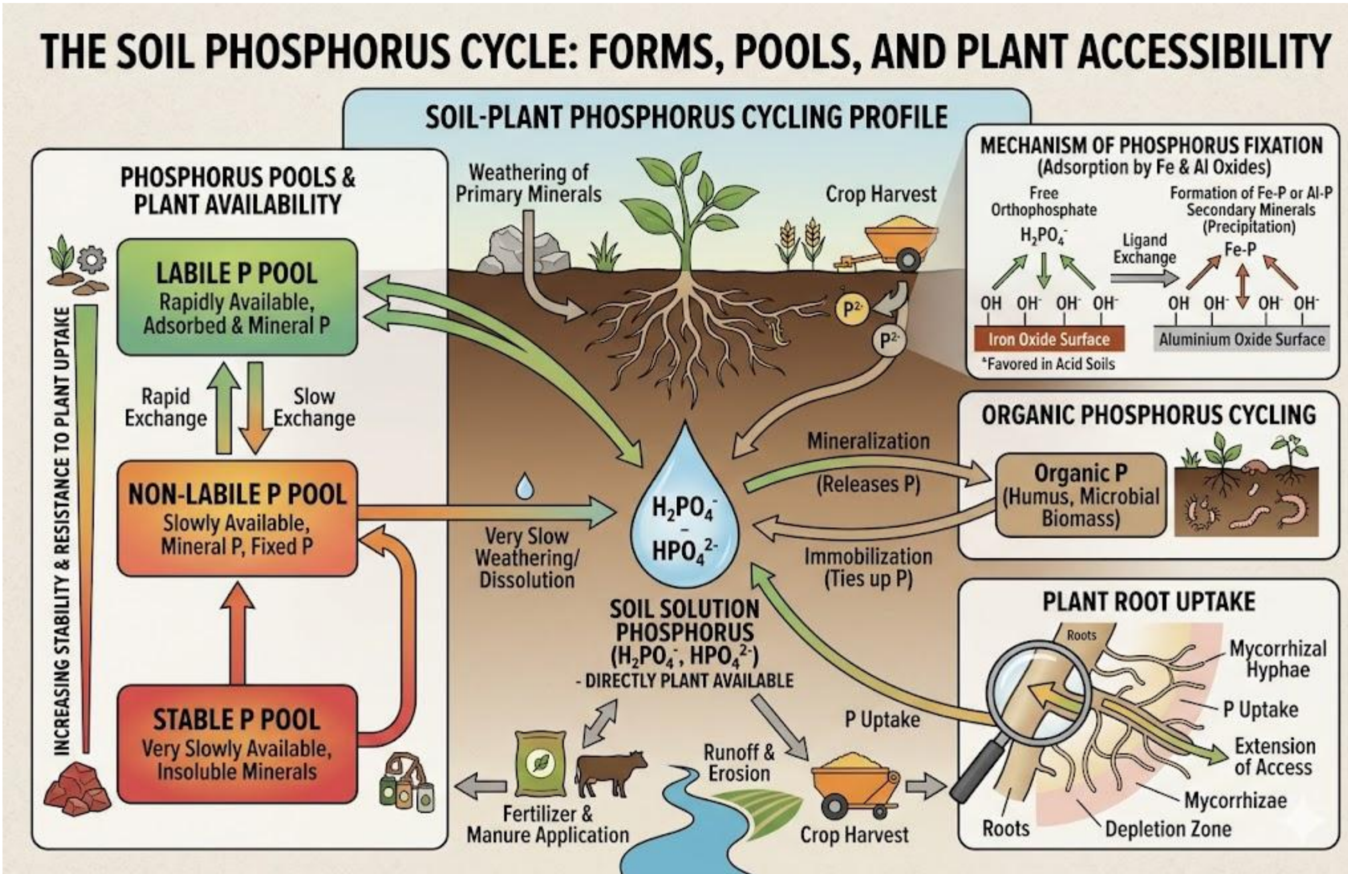

Figure 4.8: Diagram of the phosphorus cycle showing soil solution P, labile P, non-labile P, organic P, and plant uptake pathways

4.4.2 Potassium, calcium, magnesium, and sulphur cycles

Potassium (K) in soil exists in four forms: non-exchangeable K in primary minerals (the largest pool, unavailable to plants but slowly released by weathering), exchangeable K on the CEC (readily available to plants), water-soluble K in soil solution (immediately available but small), and K fixed in the interlayer positions of 2:1 clay minerals (fixed K; unavailable but can be slowly released). Potassium does not form organic compounds in soil (unlike nitrogen and phosphorus) and is not subject to atmospheric losses, but is highly susceptible to leaching in sandy soils with low CEC. Most Nigerian soils have moderate to low available K, requiring K fertiliser application on intensive cropping systems.

Calcium (Ca) and magnesium (Mg) are both macronutrients and are the primary base cations on the CEC. In leached tropical soils they are frequently deficient (contributing to low base saturation and low pH); liming supplies both. Sulphur (S) cycles in the soil similarly to nitrogen: it occurs in organic forms in soil organic matter (released by mineralisation), in sulphate (SO42-) in soil solution (the plant-available form), and in some soils in mineral sulphide and sulphate minerals. Sulphur deficiency is increasingly common in Nigerian soils because atmospheric sulphur deposition has declined (less pollution from burning fossil fuels and bush fires), high-analysis fertilisers without sulphur are now dominant, and crop yields are higher removing more sulphur per hectare. Legumes and cereals on low-organic-matter sandy soils are most vulnerable.

Fill in the blank: ________ deficiency in Nigerian soils is increasingly common because atmospheric sulphur deposition has declined, high-analysis fertilisers without sulphur are widely used, and crop removal has increased.

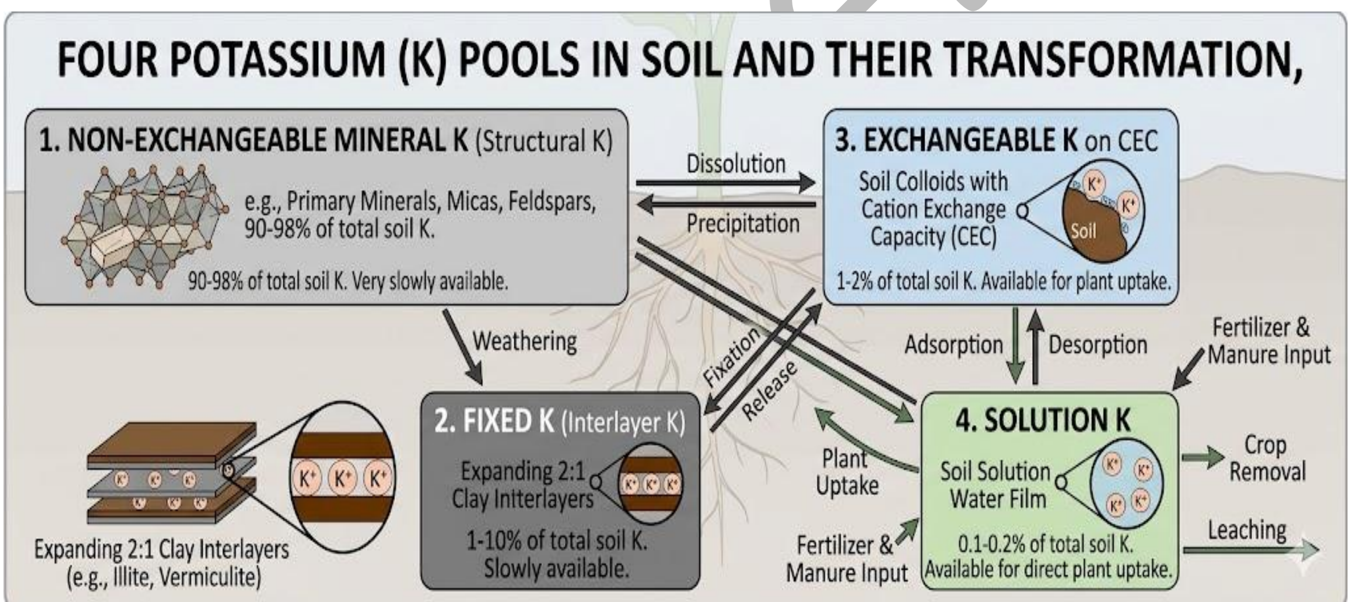

Figure 4.9: Diagram showing the potassium cycle in soil with the four K pools and their transformations

4.4.3 Micronutrient cycles and nutrient management principles

Micronutrients (iron, zinc, copper, manganese, boron, molybdenum, chlorine, and nickel) are required by plants in very small amounts but are essential for specific enzymatic and physiological functions. Micronutrient availability in soil is strongly controlled by soil pH: iron, zinc, copper, and manganese become less available as pH rises above 7.0; molybdenum and boron become less available at low pH. Zinc deficiency is one of the most widespread micronutrient constraints on crop production globally and in Nigeria, particularly in highly weathered, calcareous, or intensively cropped soils.

The principles of integrated nutrient management (INM) provide the framework for addressing the multiple nutrient constraints of Nigerian soils simultaneously. INM combines organic inputs (manure, compost, crop residues) with judicious use of inorganic fertilisers to meet crop nutrient requirements while building soil organic matter and long-term fertility. The four core principles of INM are: (1) soil testing to identify limiting nutrients before applying fertilisers; (2) matching nutrient supply (organic plus inorganic) to crop demand across the growing season; (3) maintaining soil organic matter as the foundation of biological fertility; and (4) avoiding nutrient losses by correct timing, placement, and rate of fertiliser application. INM is more economically efficient and environmentally sustainable than reliance on synthetic fertilisers alone or organic inputs alone.

Fill in the blank: Integrated nutrient management (INM) combines ________ inputs with judicious inorganic fertiliser use to meet crop requirements while building soil organic matter and long-term soil fertility.

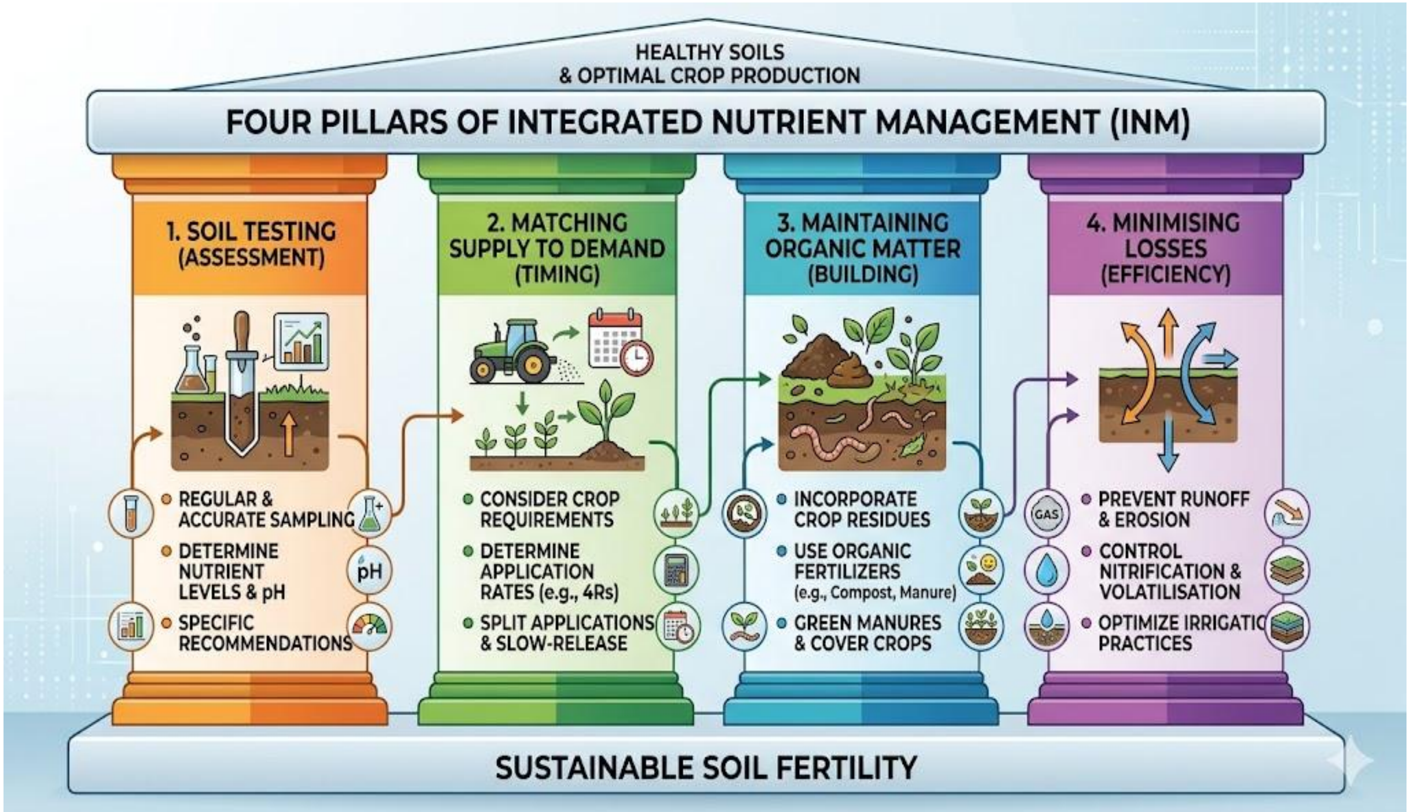

Figure 4.10: Diagram showing the four principles of integrated nutrient management and their relationship to crop productivity and soil health

Pilot questions 4.4

1. Explain why the phosphorus cycle differs fundamentally from the nitrogen cycle.
2. Explain why phosphorus fixation is a major problem in highly weathered tropical soils.
3. Describe two management strategies to improve phosphorus availability in highly weathered Nigerian soils.
4. Explain why sulphur deficiency is increasingly common in Nigerian crop production.
5. State the four core principles of integrated nutrient management.

Series Summary

This Series has covered the physical and chemical systems that make soil a functional medium for plant growth: water, air, temperature, and nutrient cycles. We began with soil water, describing the three forms (gravitational, capillary, and hygroscopic), defining soil water potential and the key reference points of field capacity and permanent wilting point, and explaining plant-available water and how texture and organic matter influence it. We then described water movement processes (infiltration, percolation, capillary rise, and preferential flow) and their consequences for drainage, nutrient leaching, and salinity.

Following that, we covered soil air and temperature: the composition of soil air, the importance of oxygen for root and microbial function, the mechanisms of aeration by diffusion and mass flow, the factors controlling soil temperature, and the use of mulching to moderate temperature extremes in Nigerian dry season conditions. We then studied the nitrogen cycle in detail, covering all six transformation processes, biological nitrogen fixation by Rhizobium, nitrogen mineralisation and its controls, and the three main loss pathways (nitrate leaching, denitrification, and ammonia volatilisation) with management options to minimise each. Finally, we covered the phosphorus cycle and phosphorus fixation in tropical soils, the potassium, calcium, magnesium, and sulphur cycles, micronutrient availability and the pH-availability relationship, and the four principles of integrated nutrient management. By completing this Series, you should now be able to achieve all nine Series Learning Outcomes (SLO 4.1 to SLO 4.9).

Glossary of Terms

- **Ammonia volatilisation:** the loss of nitrogen as ammonia gas (NH3) from surface-applied urea or ammonium fertilisers, especially on alkaline or warm soils without incorporation; reduced by incorporating fertiliser into the soil.
- **Capillary rise:** the upward movement of water through fine soil pores from a water table or saturated zone, driven by surface tension; can supply plant roots but may also cause surface salinisation.

- **Capillary water:** soil water held in fine pores (0.0002 to 0.05 mm diameter) by surface tension forces against gravity; the primary source of plant-available water.
- **Denitrification:** the microbial reduction of nitrate (NO_3^-) to nitrogen gas (N_2) and nitrous oxide (N_2O) under anaerobic conditions; a major nitrogen loss pathway from waterlogged soils.
- **Diffusion:** the movement of gas or solute molecules down their concentration gradient; the primary mechanism of soil aeration, moving O_2 into the soil and CO_2 out of the soil.
- **Field capacity (FC):** the volumetric water content of a soil after free drainage ceases (one to three days after saturation); the upper limit of plant-available water, corresponding to a water potential of approximately -10 to -33 kPa.
- **Gravitational water:** soil water held in large macropores that drains freely under gravity after rainfall; generally unavailable to plants before drainage; moves by percolation.
- **Hygroscopic water:** soil water held as a thin film on particle surfaces by strong adsorption forces; essentially unavailable to plants.
- **Infiltration:** the entry of water into the soil from the surface; measured as infiltration rate (mm/hour); controlled by soil texture, structure, organic matter content, and antecedent moisture.
- **Integrated nutrient management (INM):** a soil fertility management approach combining organic inputs and inorganic fertilisers to meet crop nutrient requirements while building soil organic matter and minimising nutrient losses.
- **Labile phosphorus:** phosphorus loosely adsorbed on soil particle surfaces in rapid equilibrium with soil solution; moderately available to plants and serves as a buffer replenishing solution phosphorus.
- **Mineralisation (nitrogen):** the release of inorganic ammonium from organic nitrogen compounds by soil microorganisms during decomposition; the primary process supplying plant-available nitrogen from soil organic matter.
- **Nitrate leaching:** the movement of nitrate ions downward through the soil profile with percolating water, below the root zone into groundwater; particularly severe on sandy soils in high-rainfall periods.
- **Nitrification:** the two-step oxidation of ammonium to nitrate by Nitrosomonas and Nitrobacter bacteria; produces nitrate (leachable) and releases H^+ (acidifying).

- **Non-labile phosphorus:** phosphorus strongly fixed to iron and aluminium oxides or locked in primary mineral apatite; the largest soil phosphorus pool but essentially unavailable to plants in the short term.
- **Percolation:** the downward movement of water through already saturated or near-saturated soil by gravity; the primary mechanism of deep drainage, leaching, and groundwater recharge.
- **Permanent wilting point (PWP):** the volumetric water content at which plants can no longer extract water at a rate sufficient to maintain turgor, wilting irreversibly; corresponds to approximately -1,500 kPa water potential.
- **Phosphorus fixation:** the reaction of soil solution phosphate with iron and aluminium oxides to form insoluble iron phosphate and aluminium phosphate compounds; the primary constraint on phosphorus availability in highly weathered tropical soils.
- **Plant-available water (PAW):** the difference in volumetric water content between field capacity and permanent wilting point; the water that plants can actually extract from the soil; expressed as % or mm/m depth.
- **Preferential flow:** the rapid movement of water and solutes through macropores (earthworm channels, root channels, cracks) bypassing the fine pore matrix; reduces both plant water availability and contaminant removal.
- **Soil aeration:** the exchange of gases between the soil and the atmosphere, replenishing oxygen consumed by root and microbial respiration and removing accumulated CO_2; primarily by diffusion.
- **Soil water potential:** the energy required to extract a unit volume of water from the soil relative to pure free water; measured in kPa; becomes more negative as soil dries; determines plant water availability.
- **Sulphur deficiency:** an increasingly common nutrient constraint in Nigerian soils resulting from reduced atmospheric sulphur deposition, use of sulphur-free high-analysis fertilisers, and increased crop removal.
- **Urease:** an enzyme produced by soil microorganisms that catalyses the hydrolysis of urea fertiliser to ammonium carbonate; the first step toward ammonia volatilisation from surface-applied urea.

Concept Check Questions [Series 4]

Objective Questions

1. Soil water potential at the permanent wilting point is approximately ________ kPa. (Linked to SLO 4.1)
2. Plant-available water = ________ capacity minus the permanent wilting point. (Linked to SLO 4.2)
3. Soil air has much higher ________ dioxide content than atmospheric air because of root and microbial respiration. (Linked to SLO 4.4)
4. Nitrate is more susceptible to leaching than ammonium because its negative charge prevents it from being held on the negatively charged ________ sites. (Linked to SLO 4.7)
5. ________ fixation by iron and aluminium oxides is the primary constraint on phosphorus availability in highly weathered tropical soils. (Linked to SLO 4.8)

Short-Answer Questions

1. Define field capacity and permanent wilting point and explain why the plant-available water of a clay soil is not necessarily much higher than that of a sandy loam. (Linked to SLO 4.2)
2. Explain why oxygen is essential for plant root function and describe two consequences of its depletion in waterlogged soils. (Linked to SLO 4.4)
3. Describe the process of denitrification and explain why it is both a nitrogen loss problem and a climate concern. (Linked to SLO 4.7)
4. Explain why phosphorus fixation is a major problem in Nigerian Alfisols and Ultisols. (Linked to SLO 4.8)
5. State the four core principles of integrated nutrient management. (Linked to SLO 4.9)

Long-Answer Questions

1. Analyse soil water and soil air as the immediate physical resources delivered by soil to plants, explaining the forms and energy status of soil water, the concepts of field capacity, permanent wilting point, and plant-available water, the processes of water movement, and the importance of soil aeration, gas exchange, and temperature for plant growth. (Linked to SLOs 4.1, 4.2, 4.3, 4.4, 4.5)

2. Discuss the nitrogen cycle in the soil-plant system, describing all six major transformation processes, explaining biological nitrogen fixation and mineralisation in the context of Nigerian farming systems, and identifying the three main nitrogen loss pathways with management strategies to minimise each. (Linked to SLOs 4.6, 4.7)
3. Evaluate the phosphorus and other nutrient cycles in tropical soils, explaining why phosphorus availability is frequently limiting, describing the management strategies to improve phosphorus efficiency, and discussing the sulphur, potassium, calcium, and micronutrient cycles in the context of integrated nutrient management for Nigerian agriculture. (Linked to SLOs 4.8, 4.9)

Answers to Concept Check Questions [Series 4]

Objective Questions

1. -1,500.
2. Field.
3. Carbon.
4. Exchange.
5. Phosphorus.

Short-Answer Questions

1. Field capacity (FC) is the volumetric water content after free drainage ceases (one to three days after saturation), corresponding to approximately -10 to -33 kPa; permanent wilting point (PWP) is the water content at which plants can no longer extract water, corresponding to approximately -1,500 kPa. Clay soils hold much more total water than sandy loams at both FC and PWP because their large surface area and fine pores retain water strongly; however, because clay also retains a large quantity of water at the PWP (that plants cannot access), the difference (PAW = FC - PWP) is not proportionally larger; a sandy loam may have PAW of 80 to 120 mm/m and a clay 100 to 140 mm/m — a modest difference despite the clay holding double the total water.
2. Plant roots require oxygen to sustain aerobic respiration, which provides the energy for active transport of mineral nutrients across root cell membranes; without oxygen, roots can only

generate energy by anaerobic fermentation, producing far less ATP and causing accumulation of ethanol and acetaldehyde that damage root cells. Two consequences of oxygen depletion in waterlogged soils: iron is chemically reduced from Fe^{3+} to Fe^{2+}, which is soluble and potentially toxic to roots at high concentrations; nitrogen is lost through denitrification, in which anaerobic bacteria convert nitrate to N_2 and N_2O gas, removing plant-available nitrogen from the soil.

3. Denitrification is the reduction of nitrate (NO_3^-) to nitrogen gas (N_2) and nitrous oxide (N_2O) by anaerobic bacteria (Pseudomonas, Paracoccus) in waterlogged or near-saturated soil zones with adequate organic carbon as energy; it is a nitrogen loss problem because it removes plant-available nitrogen from the soil permanently as gas; it is a climate concern because nitrous oxide (N_2O) is a potent greenhouse gas with approximately 300 times the global warming potential of CO_2 over 100 years, and agricultural soils are the largest anthropogenic source of N_2O emissions globally.
4. Nigerian Alfisols and Ultisols are highly weathered soils dominated by iron and aluminium oxides and kaolinite clay; the iron and aluminium oxide surfaces have a very high affinity for phosphate ions, which are held in insoluble iron phosphate and aluminium phosphate compounds through a process called phosphorus fixation; the more iron and aluminium oxide present (as in these highly weathered soils) the more severe the fixation; the practical consequence is that only 10 to 15 per cent of applied phosphate fertiliser becomes plant-available in the season of application, making phosphorus management both challenging and expensive for Nigerian farmers.
5. The four core INM principles are: (1) soil testing to identify limiting nutrients before applying fertilisers; (2) matching nutrient supply from organic and inorganic sources to crop demand across the growing season; (3) maintaining soil organic matter as the foundation of long-term biological fertility; and (4) avoiding nutrient losses through correct timing, placement, and rate of fertiliser application.

Long-Answer Questions

1. Basic response: Soil water forms: gravitational (macropores, drains freely, unavailable); capillary (fine pores, surface tension, plant-available); hygroscopic (surface films, unavailable). Water potential: from near 0 at saturation to -1,500 kPa at PWP; more negative = less available. PAW = FC - PWP; sandy soils have lower total storage but similar PAW to clay soils. Water movement: infiltration (entry at surface, controlled by texture, structure, crusting); percolation (downward drainage, leaches nutrients); capillary rise (upward from

water table, salinity risk); preferential flow (macropores). Soil air: lower O_2 (15 to 20%), much higher CO_2 (0.3 to 5%) than atmosphere; O_2 essential for root respiration; aeration by diffusion (primary) and mass flow. Soil temperature: controlled by radiation, colour, water, cover; mulching moderates extremes.

2. Value-added response: The most practically significant interaction between water and nutrients for Nigerian farmers is the timing of nitrate fertiliser application relative to rainfall events. A urea application that nitrifies to nitrate three weeks before a heavy rainfall event can lose 30 to 50 per cent of the applied nitrogen to leaching in sandy savanna soils, converting an expensive fertiliser input into groundwater pollution rather than crop yield. Teaching students to time split nitrogen applications to coincide with peak crop demand (rather than applying all nitrogen at planting) and to prefer ammonium sulphate over urea on sandy soils in high-rainfall areas are the most directly actionable water-nitrogen management decisions arising from this part of the course.
3. Basic response: Six nitrogen cycle processes: fixation (N_2 to NH_4^+ by biological or industrial means), mineralisation (organic N to NH_4^+), nitrification (NH_4^+ to NO_3^-), plant uptake (NO_3^- and NH_4^+ by roots), immobilisation (mineral N into microbial biomass), losses (leaching, denitrification, volatilisation). BNF: symbiotic Rhizobium in legume nodules (100 to 200 kg N/ha for soybean); free-living Azotobacter. Mineralisation: controlled by temperature, moisture, C:N ratio (below 25:1 = net N release). Nitrogen losses: nitrate leaching (NO_3^- negative charge, no exchange site retention, severe in sandy soils after heavy rain); denitrification (anaerobic bacteria, NO_3^- to N_2 + N_2O in waterlogged zones); volatilisation (urea hydrolysis to NH_4^+, then NH_3 at high pH or high temperature). Management: split applications, incorporate urea, avoid waterlogging, use legumes in rotation.
4. Value-added response: The greatest leverage point in Nigerian nitrogen management is not the choice between organic and inorganic nitrogen sources but the use of legumes in rotation. A cowpea or soybean crop that fixes 100 to 150 kg N/ha leaves a substantial nitrogen legacy in the soil for the subsequent cereal crop; field experiments in the Nigerian Guinea savanna consistently show that maize following soybean responds less to applied nitrogen fertiliser than maize in continuous monoculture, because the soybean rotation nitrogen reduces the nitrogen deficit the cereal must fill from fertiliser. Teaching students to quantify and value this rotation nitrogen benefit is one of the most economically significant outcomes of studying the nitrogen cycle.

5. Basic response: Phosphorus cycle: no atmospheric reservoir; three pools — solution phosphate (plant-available, tiny), labile adsorbed (buffer), non-labile fixed (largest, unavailable). Phosphorus fixation by Fe and Al oxides: dominant in Alfisols and Ultisols; efficiency as low as 10 to 15%. Management: band application, combine with organic matter, raise pH by liming, use rock phosphate in acid soils, encourage AMF. Potassium cycle: four pools (non-exchangeable mineral, exchangeable on CEC, solution, fixed in clay interlayers); leaching risk in sandy low-CEC soils. Calcium and magnesium: base cations, deficient in leached tropical soils, supplied by liming. Sulphur: cycle similar to N (organic, mineralisation, sulphate SO42-); deficiency increasing due to reduced atmospheric S, sulphur-free fertilisers, higher crop yields. Micronutrients: pH-controlled availability; Zn deficiency most widespread. INM: soil testing, match supply to demand, maintain SOM, minimise losses.
6. Value-added response: The phosphorus fixation problem in Nigerian soils reveals a fundamental economic paradox in smallholder fertiliser use: the farmer pays for 100 per cent of the phosphorus applied but captures only 10 to 15 per cent of it in the current season's crop. The remaining 85 to 90 per cent is not lost from the system (unlike leached nitrogen) but is fixed in the soil and released very slowly over subsequent years. This means that continuous phosphate application builds a reservoir of residual phosphorus in the soil that reduces the fertiliser requirement in subsequent seasons. Teaching students to account for residual phosphorus in fertiliser recommendations (reducing application rates on soils with a history of phosphate application) demonstrates an understanding of the phosphorus cycle that translates directly into improved economic advice for farmers.

Answers to Pilot Questions [Series 4]

Part 4.1: Soil Water

1. Gravitational water is held in large macropores and drains freely under gravity after rainfall ceases, typically within one to three days; it is generally not available to plants before draining. Capillary water is held in fine pores (0.0002 to 0.05 mm) by surface tension forces against gravity; it is the primary source of plant-available water. Hygroscopic water is held as a thin film on particle surfaces by strong adsorption forces and is essentially unavailable to plants.

2. Soil water potential describes the energy status of water in the soil relative to pure free water; it is zero at saturation and becomes increasingly negative as the soil dries; it becomes more negative because as gravitational and capillary water drains or is extracted by roots, only increasingly tightly bound water remains; the surface tension forces on thinner films in smaller pores require more energy (more negative potential) to overcome and extract the water.
3. Field capacity (FC) is the volumetric water content after excess gravitational water has drained away (one to three days after saturation), corresponding to approximately -10 to -33 kPa; it represents the upper limit of plant-available water storage. Permanent wilting point (PWP) is the water content at which plants can no longer maintain sufficient water uptake to sustain turgor and wilt irreversibly, corresponding to approximately -1,500 kPa; it is the lower limit of plant-available water. Plant-available water (PAW) = FC - PWP, expressed as volumetric percentage or mm of water per metre of soil depth.
4. Sandy soils have lower PWP water content than clay soils (less surface area to hold residual water at -1,500 kPa), but they also have lower FC water content (large pores drain at lower suction); the difference (PAW = FC - PWP) is therefore not dramatically smaller for sandy soils than for loam soils; additionally, clay soils hold a large proportion of their water so tightly (at high suction) that it is unavailable to plants, reducing the effective advantage of the higher total water storage that clay provides.
5. Surface crusting occurs when raindrops impact the bare soil surface, dispersing surface aggregates and washing fine particles into pores; as the soil dries, these fine particles form a dense, low-porosity crust at the surface; this crust has very low hydraulic conductivity (few large pores remain), so subsequent rain cannot enter the soil quickly enough and instead runs off the surface, taking eroded topsoil with it; crops germinating through the crust also suffer mechanical impedance to seedling emergence.

Part 4.2: Soil Air and Soil Temperature

1. Any three: lower oxygen content (15 to 20 per cent versus 21 per cent in the atmosphere) because roots and microorganisms continuously consume O2; much higher carbon dioxide content (0.3 to 5 per cent versus 0.04 per cent) because root and microbial respiration continuously produce CO2; higher water vapour content (near saturation in the soil pore space versus variable in the atmosphere); may contain trace gases from anaerobic

decomposition (methane, hydrogen sulphide, nitrous oxide) absent from normal atmospheric air.

2. Plant roots require oxygen for aerobic respiration, which generates the ATP energy needed for active transport of mineral nutrient ions across root cell membranes; when soil oxygen falls below approximately 10 per cent, root respiration is impaired and roots switch to anaerobic fermentation, producing far less ATP and generating ethanol and acetaldehyde, which are toxic to root cells. Two consequences of depletion: iron is reduced to soluble Fe^{2+} which can accumulate to toxic concentrations; nitrogen is lost through denitrification by anaerobic bacteria that use nitrate as an oxygen substitute, producing N_2 and N_2O gas.
3. Soil aeration is the exchange of oxygen and carbon dioxide between the soil pore space and the atmosphere; diffusion is the movement of gas molecules down their concentration gradient — since O_2 is continuously consumed by root respiration and microbial decomposition, its concentration in soil air falls below atmospheric (creating a concentration gradient that drives O_2 inward from the atmosphere); simultaneously, CO_2 accumulates in soil air above atmospheric levels (creating a gradient that drives CO_2 outward); diffusion along these gradients is the primary mechanism maintaining adequate oxygen for roots and microorganisms under non-saturated conditions.
4. Compaction reduces soil aeration by crushing and destroying macropores (the large inter-aggregate spaces that conduct gas most rapidly); when macropores are lost, the remaining fine pore space is easily filled with water and gas diffusion rates fall dramatically because oxygen diffuses approximately 10,000 times more slowly through water than through air; one management practice to restore aeration: subsoiling (deep tillage to 40 to 60 cm depth) to shatter the compacted layer and re-create macropores, though the effect is temporary unless the cause of compaction (traffic on wet soil) is addressed.
5. In Nigerian dry season conditions, bare soil surface temperatures can reach 45 to 55°C, which kills seeds, damages seedling roots near the surface, and desiccates the soil surface; mulching works by: intercepting solar radiation before it reaches the soil surface (reducing daytime maximum temperature by 5 to 15°C); slowing convective heat loss at night (moderating minimum temperature); reducing evaporation from the soil surface (keeping the surface moist and increasing the heat capacity of the soil so it warms more slowly); the net effect is a more moderate, stable temperature regime that is more favourable for germination, seedling establishment, and microbial activity.

Part 4.3: The Nitrogen Cycle in Soil

1. Six major processes in sequence: (1) nitrogen fixation (atmospheric N_2 to ammonium by biological organisms or industrial process); (2) mineralisation (organic N to NH_4^+ during decomposition); (3) nitrification (NH_4^+ to NO_2^- to NO_3^- by bacteria); (4) plant uptake (roots absorb NO_3^- and NH_4^+ from soil solution); (5) immobilisation (mineral N incorporated into microbial biomass); (6) nitrogen losses (nitrate leaching, denitrification to N_2/N_2O, ammonia volatilisation, erosion).
2. Symbiotic BNF: Rhizobium bacteria form nodules on legume roots and fix atmospheric N_2 in exchange for carbohydrate from the plant; can supply 100 to 200 kg N/ha for soybean, 30 to 100 kg N/ha for cowpea; example: Rhizobium japonicum in soybean nodules. Free-living BNF: bacteria in the soil fix atmospheric N_2 without forming a plant association, but contribute much smaller amounts (typically 5 to 20 kg N/ha/year); example: Azotobacter in aerobic soils or Clostridium in anaerobic zones.
3. Nitrogen mineralisation is the release of inorganic ammonium from organic nitrogen compounds during microbial decomposition of organic matter; rate is controlled by: temperature (doubles approximately per 10°C; rapid mineralisation flush at start of rainy season in Nigerian savanna soils); moisture (optimal at approximately 60 per cent water-filled pore space; very slow in dry or waterlogged soils); C:N ratio (low C:N materials mineralise rapidly and release net nitrogen; high C:N materials decompose slowly and immobilise nitrogen initially).
4. Nitrate (NO_3^-) carries a negative charge and is therefore repelled by the negatively charged exchange sites of clay minerals and humus, which only hold positively charged cations; nitrate cannot be adsorbed to exchange sites and remains exclusively in the soil solution where it is freely mobile with percolating water. Ammonium (NH_4^+) carries a positive charge and is held on the negative exchange sites (CEC) of clay and humus, retarding its movement with water and reducing its leaching susceptibility; some ammonium is also fixed in clay mineral interlayers, further reducing its mobility.
5. Any two: split nitrogen applications — applying nitrogen fertiliser in two or three doses timed to coincide with peak crop demand (rather than as a single large application at planting) reduces the amount of mineral nitrogen present at any one time and therefore the amount susceptible to loss in a single rainfall event. Incorporating urea fertiliser — incorporating urea into the soil by mechanical mixing or irrigation rather than surface broadcasting exposes it to cooler, more buffered soil conditions that slow urease activity and reduce the pH rise that

drives volatilisation; incorporated urea is also less exposed to solar radiation that promotes surface heating and volatilisation.

Part 4.4: The Phosphorus and Other Nutrient Cycles

1. The phosphorus cycle differs from the nitrogen cycle because phosphorus has no atmospheric reservoir: all the phosphorus on Earth is in rocks, soil minerals, organic matter, and living organisms; there is no gaseous phase to replenish phosphorus from the atmosphere (unlike nitrogen gas, which constitutes 78 per cent of the atmosphere and is accessible through biological fixation); this means that phosphorus lost from the soil through leaching, erosion, or crop removal is gone from the agricultural system and cannot be replaced through natural atmospheric inputs, making phosphorus management a fundamentally finite resource challenge.
2. Highly weathered tropical soils such as Nigerian Alfisols and Ultisols have undergone intensive chemical weathering that has leached away most of the calcium, magnesium, and potassium originally in the parent minerals, leaving behind iron and aluminium oxides as the dominant secondary minerals; the surface of these iron and aluminium oxide crystals has a very high affinity for phosphate ions, which are adsorbed rapidly and then precipitate as insoluble iron phosphate and aluminium phosphate compounds; the more iron and aluminium oxide surface area present (which increases with degree of weathering), the more severe this fixation and the lower the phosphorus availability.
3. Any two: band application — placing phosphate fertiliser in a narrow band alongside or below the seed row concentrates the phosphate in a zone where the fixation reaction with soil is limited (as the phosphate is not mixed with the bulk soil) and where roots actively proliferate, improving uptake efficiency by up to two to three times compared with broadcast application. Combining phosphate with organic matter — applying compost or manure with phosphate fertiliser reduces fixation because organic acids produced during decomposition compete with phosphate for iron and aluminium oxide surface sites, blocking the fixation reaction and keeping more phosphate in plant-available form.
4. Sulphur deficiency in Nigerian soils is increasingly common because: atmospheric sulphur deposition has declined as coal burning and biomass burning have decreased, reducing the natural sulphur input through rainfall that formerly supplied 5 to 15 kg S/ha/year; the replacement of older compound fertilisers that contained sulphate (ammonium sulphate,

single superphosphate) with higher-analysis sulphur-free fertilisers (urea, triple superphosphate, diammonium phosphate) has eliminated an important fertiliser sulphur source; and higher crop yields per hectare remove more sulphur per season, exceeding the natural mineralisation supply.

5. The four core INM principles are: (1) soil testing before each cropping season to identify which nutrients are limiting and at what level, so fertiliser applications are targeted at actual deficiencies rather than applied as a blanket; (2) matching nutrient supply from organic and inorganic sources to crop demand across the growing season, including timing applications to coincide with periods of peak crop uptake; (3) maintaining soil organic matter as the foundation of long-term biological fertility, supplying nutrients, building structure, and supporting soil organisms; (4) minimising nutrient losses by correct timing (avoid applying before heavy rain), placement (incorporate fertilisers), and rate (do not over-apply beyond crop demand).

References and Attributions [Series 4]

Textual References (Books and External Sources)

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- FAO (Food and Agriculture Organization of the United Nations). (2025). Guidelines for sustainable agriculture. FAO.

Figures, Plates, Tables, and Boxes

- Figure 4.1: Soil water retention curve Attribution: AI generated using prompt "Generate a soil moisture retention curve showing gravitational water, plant-available capillary water, and hygroscopic water zones, with field capacity and permanent wilting point marked." Suggested OER search string: "soil water forms plant available water field capacity wilting point retention curve OER".
- Table 4.1: Field capacity and plant-available water by texture Attribution: AI generated using prompt "Generate a table showing field capacity, permanent wilting point, and plant-available water values for sandy, sandy loam, loam, clay loam, and clay soils." Suggested OER search string: "soil textural class field capacity wilting point plant available water table OER".
- Figure 4.2: Soil water movement diagram Attribution: AI generated using prompt "Generate a cross-section diagram of a soil profile showing rainfall infiltration at the surface, downward percolation to the water table, and capillary rise upward from the water table." Suggested OER search string: "soil water movement infiltration percolation capillary rise diagram OER".
- Table 4.2: Soil air versus atmospheric air composition Attribution: AI generated using prompt "Generate a table comparing atmospheric air and typical soil air composition for O2, CO2, N2,

and water vapour with significance notes." Suggested OER search string: "soil air composition versus atmospheric air O2 CO2 comparison table OER".

- Figure 4.3: Soil aeration gas exchange diagram Attribution: AI generated using prompt "Generate a diagram showing gas exchange between soil and atmosphere including O2 diffusion inward and CO2 diffusion outward through soil macropores." Suggested OER search string: "soil aeration gas exchange diffusion O2 CO2 macropores diagram OER".
- Figure 4.4: Soil temperature factors diagram Attribution: AI generated using prompt "Generate a diagram showing factors controlling soil temperature including solar radiation, soil colour, water content, mulch, vegetation, slope, and depth." Suggested OER search string: "soil temperature factors solar radiation mulch colour water content OER diagram".
- Figure 4.5: Nitrogen cycle diagram Attribution: AI generated using prompt "Generate a diagram of the nitrogen cycle showing atmospheric N2, biological nitrogen fixation, mineralisation, nitrification, plant uptake, immobilisation, denitrification, and leaching." Suggested OER search string: "nitrogen cycle soil plant atmosphere fixation mineralisation nitrification OER diagram".
- Figure 4.6: BNF and nitrogen fate diagram Attribution: AI generated using prompt "Generate a diagram showing Rhizobium nitrogen fixation in legume nodules, fixed nitrogen flow to plant and soil, crop residue decomposition, and nitrogen uptake by the next crop." Suggested OER search string: "biological nitrogen fixation Rhizobium legume nodules soil nitrogen cycle OER".
- Figure 4.7: Nitrogen loss pathways diagram Attribution: AI generated using prompt "Generate a three-panel diagram showing nitrogen loss pathways: nitrate leaching downward, denitrification to N2 and N2O, and ammonia volatilisation from surface urea." Suggested OER search string: "nitrogen losses leaching denitrification volatilisation pathways diagram OER".
- Figure 4.8: Phosphorus cycle diagram Attribution: AI generated using prompt "Generate a diagram of the phosphorus cycle showing soil solution phosphorus, labile and non-labile pools, organic phosphorus, plant uptake, and fixation by iron and aluminium oxides." Suggested OER search string: "phosphorus cycle soil solution labile non-labile fixation organic plant uptake OER".
- Figure 4.9: Potassium cycle diagram Attribution: AI generated using prompt "Generate a diagram showing the four potassium pools in soil: non-exchangeable mineral K, exchangeable K on CEC, solution K, and fixed K in clay interlayers, with transformation arrows." Suggested OER search string: "potassium cycle soil four pools non-exchangeable exchangeable solution fixed OER diagram".
- Figure 4.10: INM principles diagram Attribution: AI generated using prompt "Generate a four-pillar diagram showing the core principles of integrated nutrient management: soil testing,

matching supply to demand, maintaining organic matter, and minimising losses." Suggested OER search string: "integrated nutrient management INM principles soil testing organic fertiliser OER".

Course code: AGE 202

Course title: Introduction to Soil Science

Course credit load: 2 Units

Series 5: Soil Degradation, Conservation, and Sustainable Management

- **Part 5.1: Soil Erosion**
  - Sub Part 5.1.1: Types and causes of soil erosion
  - Sub Part 5.1.2: Consequences of soil erosion
  - Sub Part 5.1.3: Assessment and measurement of soil erosion
- **Part 5.2: Other Forms of Soil Degradation**
  - Sub Part 5.2.1: Soil compaction and structural degradation
  - Sub Part 5.2.2: Soil salinisation and sodification
  - Sub Part 5.2.3: Soil pollution and contamination
- **Part 5.3: Soil Conservation and Erosion Control**
  - Sub Part 5.3.1: Agronomic and vegetative conservation measures
  - Sub Part 5.3.2: Mechanical and physical conservation structures
  - Sub Part 5.3.3: Agroforestry and integrated land management
- **Part 5.4: Sustainable Soil Management**
  - Sub Part 5.4.1: Principles of sustainable soil management
  - Sub Part 5.4.2: Organic matter management and soil health indicators
  - Sub Part 5.4.3: Soil management for climate change adaptation

Introduction

Soil is a non-renewable resource on the human timescale: once degraded or eroded, it takes thousands of years to reform. Yet the soils of Nigeria and much of sub-Saharan Africa are subject to accelerating degradation through erosion, compaction, salinisation, and organic matter depletion driven by population growth, inappropriate land use, and inadequate soil management. The consequences are felt directly in declining crop yields, rising food insecurity, and loss of ecosystem services. Understanding the causes, processes, and consequences of soil degradation is the foundation for designing effective conservation and management strategies.

The aim of this Series is to introduce you to the major forms of soil degradation (erosion, compaction, salinisation, and pollution), the conservation and management practices that prevent and reverse degradation, and the principles of sustainable soil management including organic matter management, soil health monitoring, and climate change adaptation.

We shall commence this Series by examining soil erosion, its causes, consequences, and measurement. Next, we will study other forms of soil degradation including compaction, salinisation, and pollution. Following that, we will cover soil conservation measures from agronomic practices to physical structures and agroforestry. Finally, we will wrap up with the principles of sustainable soil management, soil health indicators, and the role of soil management in climate change adaptation.

Series Learning Outcomes

Upon completing this Series, you should be able to:

- **SLO 5.1** describe the types and causes of soil erosion and explain the factors that influence erosion rate (Linked to Part 5.1),
- **SLO 5.2** explain the consequences of soil erosion for agricultural productivity and the environment (Linked to Part 5.1),
- **SLO 5.3** describe the methods used to assess and measure soil erosion (Linked to Part 5.1),

- **SLO 5.4** describe the causes and effects of soil compaction, salinisation, sodification, and soil pollution (Linked to Part 5.2),
- **SLO 5.5** describe agronomic and vegetative soil conservation measures and explain how they reduce erosion (Linked to Part 5.3),
- **SLO 5.6** describe mechanical and physical soil conservation structures and explain their design principles (Linked to Part 5.3),
- **SLO 5.7** explain the role of agroforestry in integrated land management and soil conservation (Linked to Part 5.3),
- **SLO 5.8** state the principles of sustainable soil management and explain the importance of organic matter management (Linked to Part 5.4), and
- **SLO 5.9** describe soil health indicators and explain how soil management contributes to climate change adaptation (Linked to Part 5.4).

5.1 Soil Erosion

5.1.1 Types and causes of soil erosion

Soil erosion is the detachment, transport, and deposition of soil particles by the action of water, wind, gravity, or tillage. It is the most widespread and damaging form of soil degradation globally and particularly in Nigeria. **Water erosion** includes: splash erosion (raindrop impact detaches soil particles and disrupts surface aggregates, creating a surface seal that reduces infiltration), sheet erosion (thin uniform removal of topsoil by shallow surface flow that is difficult to observe until significant soil loss has occurred), rill erosion (concentrated runoff cuts small channels across the slope that can be obliterated by tillage), and gully erosion (large channels formed by concentrated runoff that cannot be removed by tillage and represents the most visually dramatic form of erosion).

Wind erosion is most severe in the semi-arid northern zones of Nigeria where sparse vegetation leaves sandy soils exposed to harmattan winds. It involves the suspension of fine clay and silt particles that travel great distances, the saltation of medium sand grains that bounce along the surface, and the surface creep of coarse particles too heavy to be lifted but pushed along the ground. The most important factors controlling water erosion are rainfall erosivity (the kinetic energy of rainfall, which is very high in Nigerian storms with large drop sizes), soil erodibility (how easily the soil particles are detached and transported, determined primarily by texture, organic matter content, and aggregate stability), slope length and steepness, vegetative cover, and conservation practices. These five factors are formalised in the Universal Soil Loss Equation (USLE).

Fill in the blank: The Universal Soil Loss Equation (USLE) formalises five factors controlling water erosion: rainfall ________, soil erodibility, slope length and steepness, vegetative cover, and conservation practices.

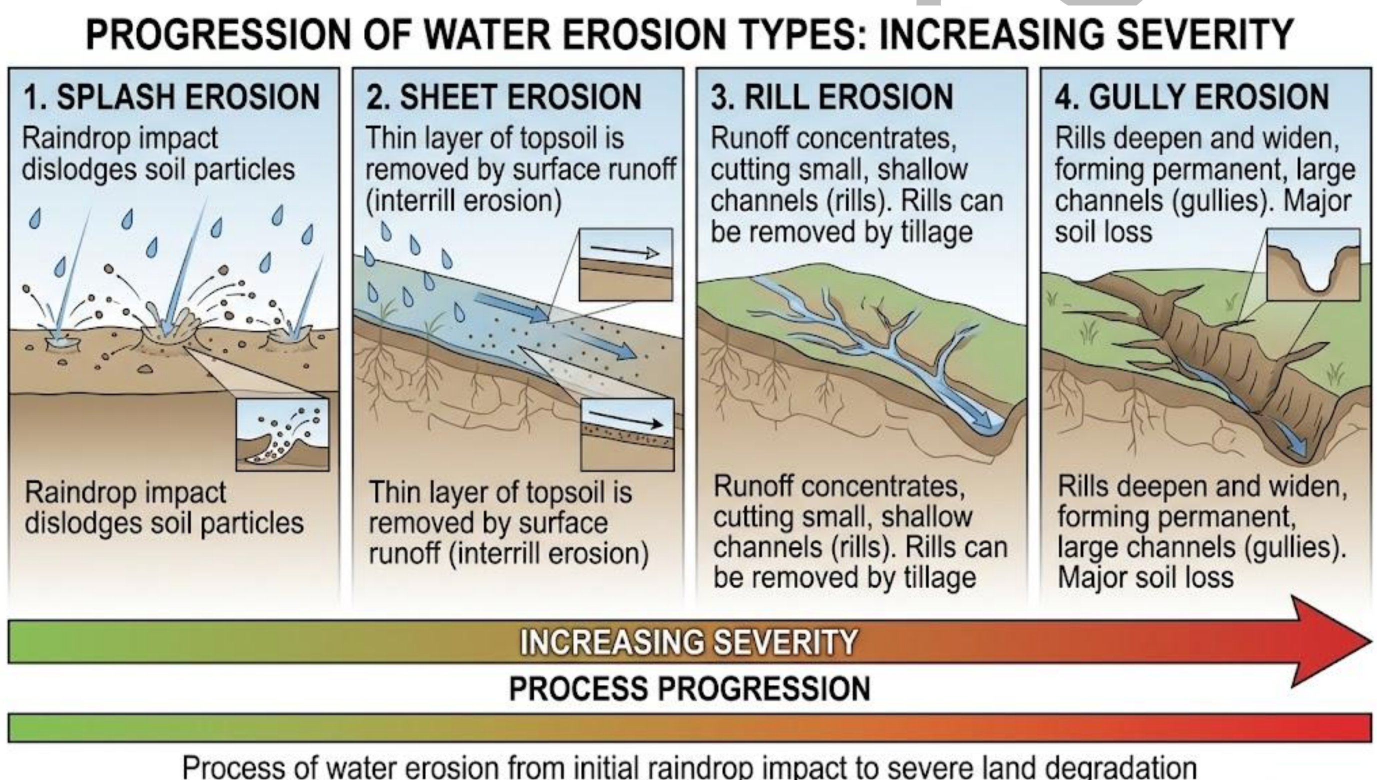

Figure 5.1: Diagram showing the four types of water erosion in sequence from splash erosion through sheet, rill, and gully erosion with increasing severity

5.1.2 Consequences of soil erosion

Soil erosion has on-site consequences directly at the point of erosion. Loss of topsoil removes the most fertile, organic-matter-rich, biologically active layer of the soil profile, reducing crop yields and increasing fertiliser requirements. In Nigerian Alfisols, erosion of 5 to 10 cm of topsoil exposes the clay-enriched, often plinthite-containing B horizon that is much harder, less fertile, and less biologically active than the eroded A horizon. Erosion also reduces the effective rooting depth available to crops, reduces plant-available water storage, and destroys soil structure, increasing runoff and accelerating further erosion in a self-reinforcing cycle.

Off-site consequences occur at locations downstream from the erosion source. Transported sediment deposits in streams, reservoirs, and irrigation canals, reducing their capacity and shortening the design life of water infrastructure (dams, irrigation systems, culverts). Sedimentation of streams increases flood risk by reducing channel capacity and increases water treatment costs. Eroded topsoil carries with it adsorbed nutrients (particularly phosphorus), organic matter, and pesticides, contributing to eutrophication and pollution of water bodies. In Nigeria, gully erosion in the south-eastern states (Anambra, Imo, Enugu, Cross River) represents one of the most severe erosion problems in West Africa, with individual gullies extending for kilometres and threatening roads, buildings, and farmland.

Fill in the blank: Off-site consequences of soil erosion include sedimentation of streams, reservoirs, and irrigation canals, which reduces their capacity and contributes to eutrophication of water bodies through transport of ________ nutrients and organic matter.

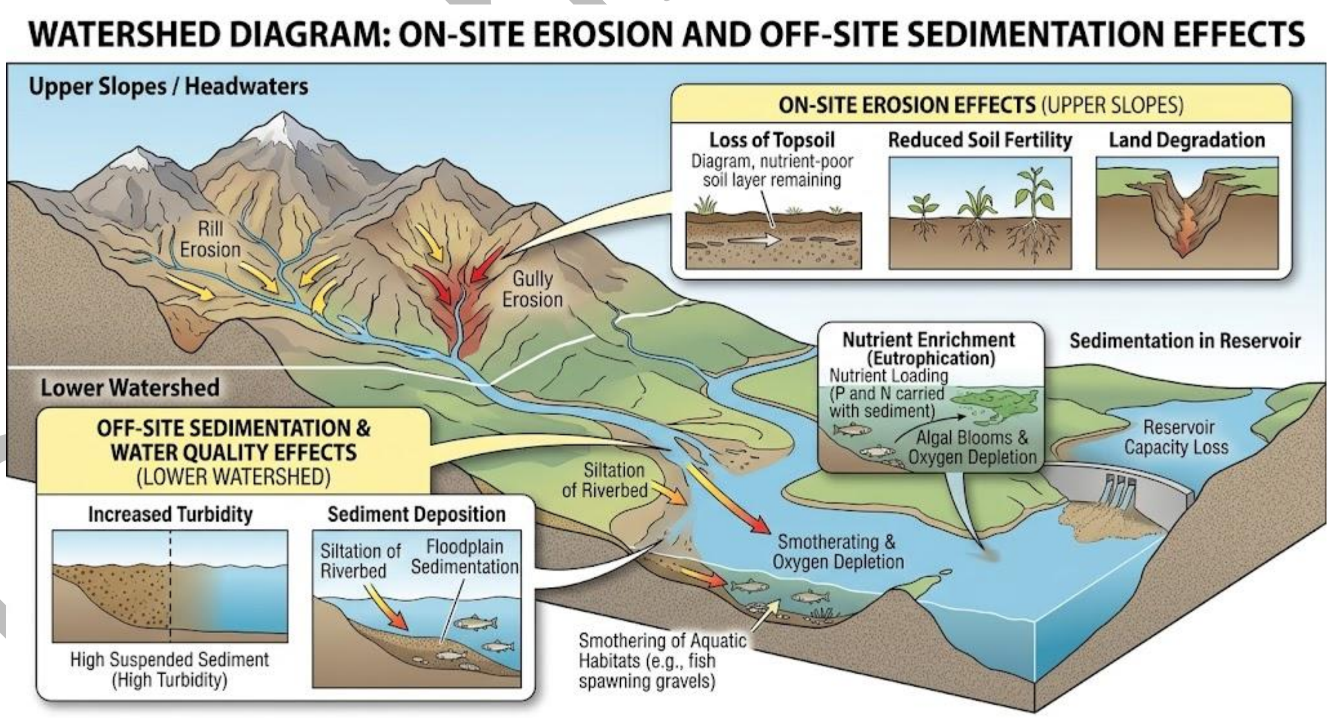

Figure 5.2: Diagram showing on-site and off-site consequences of soil erosion in a watershed

5.1.3 Assessment and measurement of soil erosion

Soil erosion can be assessed by several methods of varying precision and cost. Qualitative field assessment involves observing erosion indicators: exposed roots, pedestals (mushroom-shaped remnants where soil beneath a stone or root has been protected while surrounding soil eroded), rills and gullies, depositional fans at the base of slopes, and changes in soil colour as the lighter-coloured subsoil is exposed. These observations can be recorded systematically using a standard erosion assessment form to classify erosion severity as slight, moderate, severe, or very severe.

Quantitative measurement methods include: erosion pins (metal stakes driven into the soil with the exposed length measured periodically to detect surface lowering), sediment traps (collecting all sediment runoff from bounded plots of known area, typically in the standard USLE erosion plot of 22.1 m length), and Caesium-137 soil dating (a nuclear tracing method that uses the 1963 nuclear weapons testing fallout as a time marker to estimate long-term erosion rates from soil profiles). The Universal Soil Loss Equation (USLE: A = R x K x L x S x C x P, where A is predicted soil loss, R is rainfall erosivity, K is soil erodibility, L is slope length, S is slope steepness, C is cover and management factor, and P is support practice factor) is the most widely used predictive model for estimating erosion risk and planning conservation measures.

Fill in the blank: In the Universal Soil Loss Equation (USLE), A = R x K x L x S x C x P, the letter A represents predicted soil ________ per unit area per year.

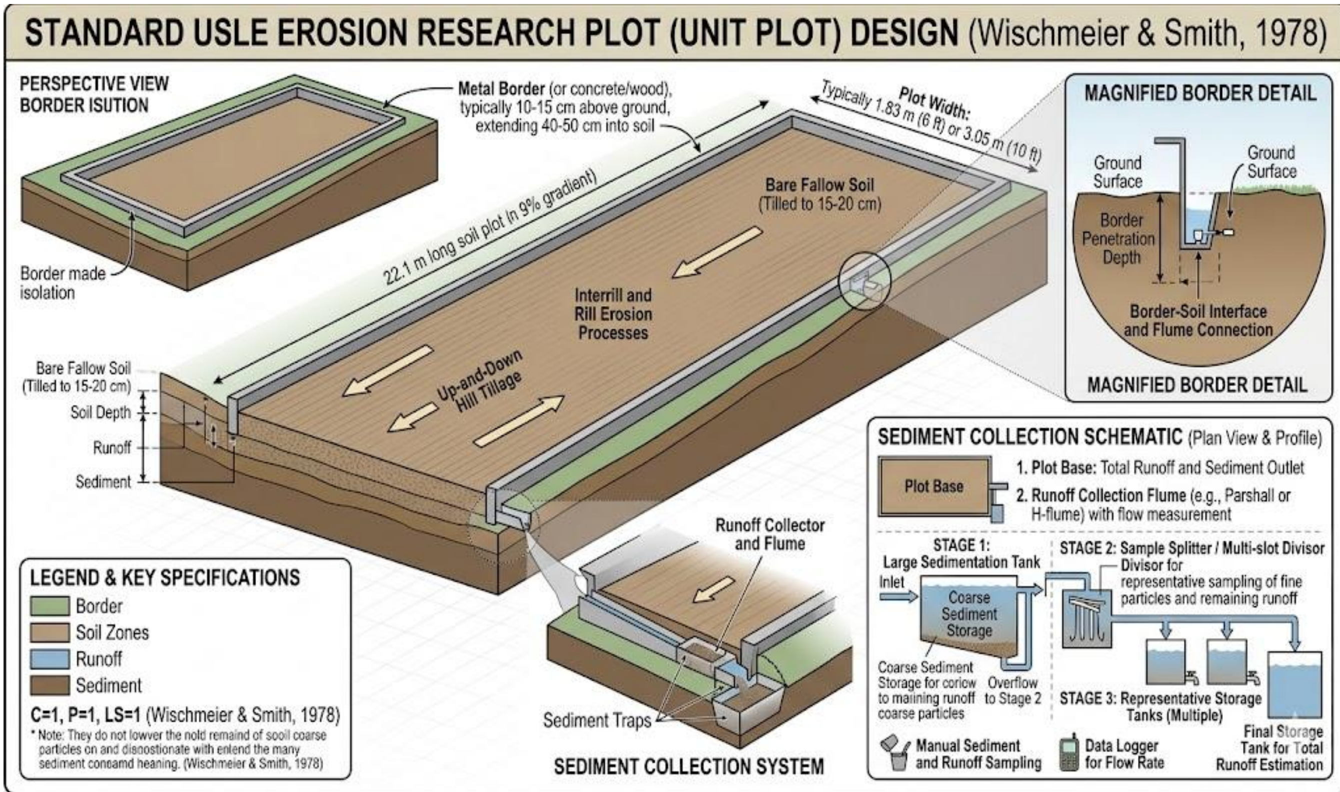

Figure 5.3: Diagram of a standard USLE erosion research plot showing its dimensions and components for sediment collection

Pilot questions 5.1

1. Name and briefly describe the four types of water erosion in order of increasing severity.
2. Explain what rainfall erosivity is and why Nigerian tropical rainfall has high erosivity.
3. State three on-site consequences of soil erosion for agricultural productivity.
4. Explain two off-site consequences of soil erosion beyond the field boundary.
5. State the components of the Universal Soil Loss Equation and explain what each factor represents.

5.2 Other Forms of Soil Degradation

5.2.1 Soil compaction and structural degradation

Soil compaction is the reduction in soil pore space and increase in bulk density caused by mechanical pressure from traffic (tractors, livestock, human foot traffic) or tillage on wet soil. Compacted soil has fewer and smaller pores, reducing water infiltration (leading to surface ponding and runoff), decreasing aeration (impairing root respiration and microbial activity), and increasing mechanical resistance to root penetration. Surface compaction (the top 5 to 20 cm) is caused by any form of traffic and is the most common form in smallholder Nigerian farming. Subsoil compaction (below 25 cm) is caused by heavy axle loads of tractors and is particularly damaging because it cannot be corrected by normal tillage.

Tillage pan (plough pan) is a dense layer that forms just below the depth of repeated ploughing, created by the smearing action of the plough bottom on moist soil. It impedes root development, drainage, and subsoil water access. Surface sealing occurs when raindrop impact destroys surface aggregates of structureless soils, washing fine particles into surface pores to form a thin dense crust that dramatically reduces infiltration. Management of compaction includes: avoiding traffic on wet soils, controlling axle loads, subsoiling, adding organic matter to stabilise aggregates against compaction, and using minimum tillage systems that leave protective residue on the surface. Prevention is far more cost-effective than remediation of compacted soil.

Fill in the blank: A tillage ________ is a dense compacted layer that forms just below the depth of repeated ploughing, created by the smearing action of the plough bottom on moist soil.

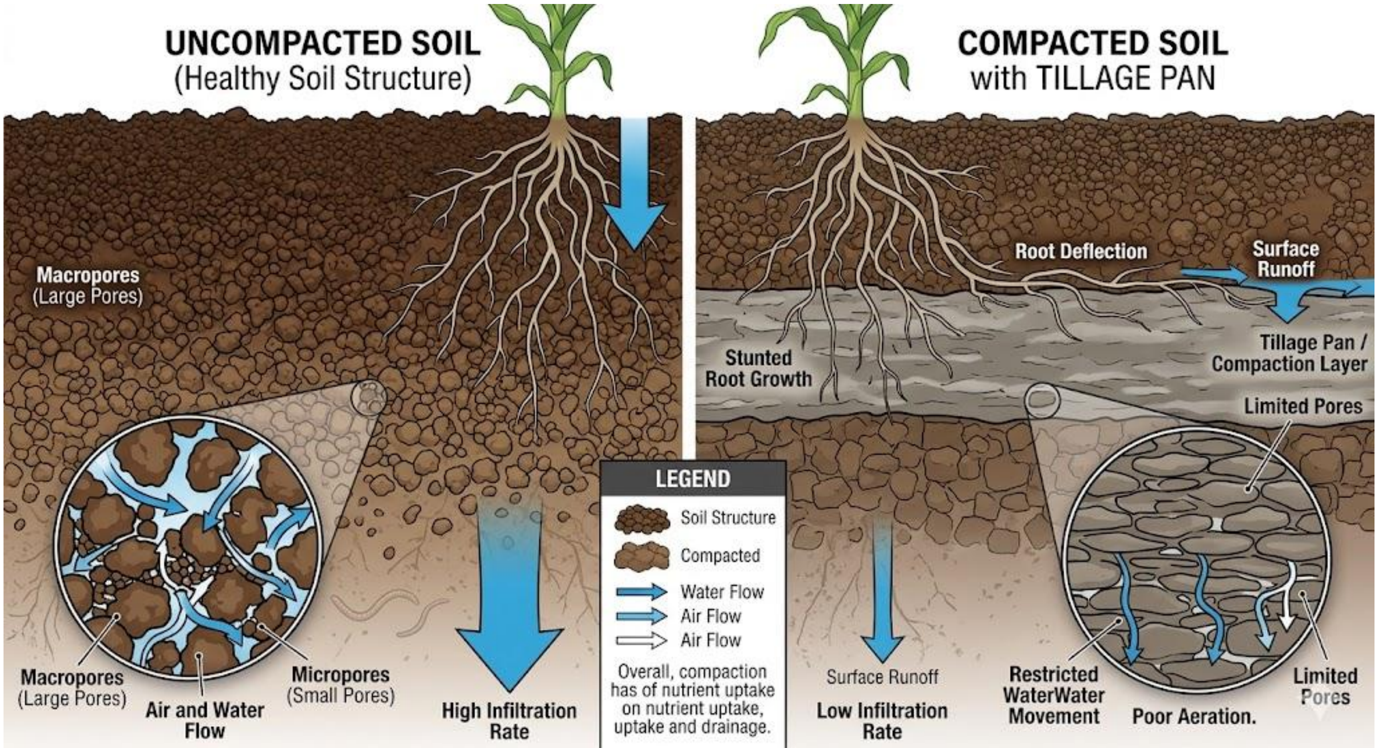

Figure 5.4: Diagram showing soil compaction effects on pore structure, root penetration, and water infiltration

5.2.2 Soil salinisation and sodification

Soil salinisation is the accumulation of soluble salts (sodium chloride, calcium chloride, magnesium sulphate, and sodium sulphate) in the soil to concentrations that inhibit plant growth. Primary salinisation occurs naturally in arid and semi-arid areas where upward capillary movement of saline groundwater deposits salts at the soil surface as water evaporates. Secondary salinisation is caused by human activity, particularly poorly managed irrigation: applying irrigation water (which contains dissolved salts) without adequate drainage causes the water table to rise, bringing dissolved salts to the surface by capillary rise.

Soil sodification is the accumulation of sodium ions (Na+) on the exchange sites of the soil, replacing calcium and magnesium. High exchangeable sodium percentage (ESP, the percentage of CEC occupied by Na+) causes clay particles to disperse (deflocculate), destroying soil structure, blocking pores, and creating an almost impermeable layer when wet and a very hard, crusted layer when dry. Sodic soils (ESP above 15) have very poor physical properties and restrict water infiltration and root penetration severely. Reclamation of saline soils requires provision of drainage and application of large amounts of fresh water to leach salts below the root zone. Reclamation of sodic soils additionally requires addition of gypsum (calcium sulphate) to replace sodium on exchange sites with calcium, followed by leaching of the displaced sodium.

Fill in the blank: Reclamation of sodic soils requires addition of ________ (calcium sulphate) to replace sodium ions on soil exchange sites with calcium, followed by leaching of the displaced sodium below the root zone.

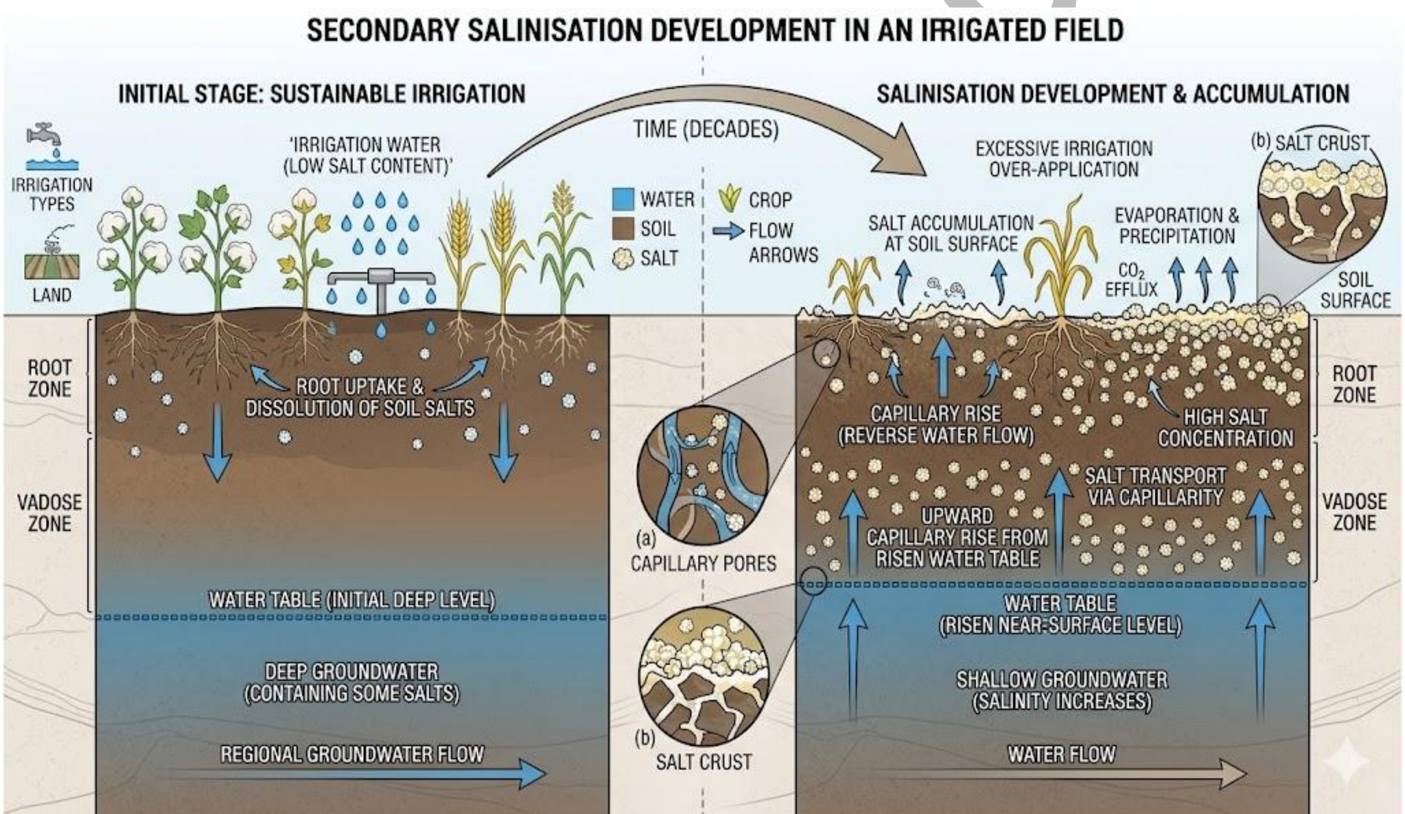

Figure 5.5: Diagram showing the development of secondary salinisation in an irrigated field with rising water table and salt accumulation at the surface

5.2.3 Soil pollution and contamination

Soil pollution is the presence of chemical or biological contaminants in soil at concentrations that are harmful to soil organisms, plants, animals, or humans. The main sources of soil pollution relevant to Nigerian agriculture are: excessive or misapplied agrochemicals (pesticides and herbicides that accumulate in the soil and may persist for months to years, affecting non-target organisms and entering food chains), heavy metals from industrial activities and mining (cadmium, lead, arsenic, mercury, and chromium contaminating soils near mining sites in Zamfara state, Jos plateau, and Delta state), indiscriminate dumping of solid and liquid industrial wastes, and petroleum hydrocarbon contamination in the Niger Delta from oil spillage.

The effects of soil contamination on agricultural production include direct phytotoxicity (certain contaminants at high concentrations kill or inhibit crop plants), accumulation of contaminants in food crops to levels that present health risks to consumers (cadmium in cereals, lead in leafy vegetables), and disruption of soil biological activity (pesticides that kill beneficial soil organisms such as earthworms and mycorrhizal fungi reduce the biological fertility of the soil). Remediation of contaminated soils is expensive and time-consuming; strategies include physical removal of contaminated soil (excavation), chemical immobilisation of contaminants (adding lime, phosphate, or organic matter to reduce solubility and bioavailability), phytoremediation (using hyperaccumulator plants to extract metals), and bioremediation (using microorganisms to degrade organic pollutants). Prevention through regulation of industrial waste disposal and responsible agrochemical use is far preferable to remediation.

Fill in the blank: ________ uses plants capable of absorbing and concentrating heavy metals in their above-ground biomass to extract contaminants from polluted soil without excavation.

Pollution Source	Examples	Effects on Soil	Effects on Crops
Agrochemicals	Excessive fertilizers, pesticides, herbicides	Nutrient imbalance, soil acidification, reduced microbial diversity	Residue accumulation, reduced crop quality, potential toxicity
Heavy metals from mining	Lead, cadmium, arsenic, mercury	Soil contamination, reduced fertility, long-term toxicity	Bioaccumulation in edible parts, health risks to consumers
Industrial waste	Chemical effluents, solid waste, plastics	Soil compaction, chemical toxicity, reduced aeration	Poor germination, stunted growth, contamination of food chain

Petroleum spills	Oil exploration, pipeline leaks, refinery discharge	Hydrocarbon contamination, hydrophobic soil layers, reduced infiltration	Crop failure, reduced yields, contamination of edible produce

Box 5.1: Main sources of soil pollution in Nigerian agriculture and their effects on soil and crop quality

Pilot questions 5.2

1. Define soil compaction and explain how it reduces crop production.
2. Explain what a tillage pan is and describe its effect on soil drainage and root development.
3. Distinguish between soil salinisation and soil sodification.
4. Explain how secondary salinisation develops in irrigated farming systems.
5. Name two sources of soil pollution in Nigeria and describe one remediation method.

5.3 Soil Conservation and Erosion Control

5.3.1 Agronomic and vegetative conservation measures

Agronomic conservation measures modify cropping and tillage practices to reduce erosion without requiring physical structures. They include: **cover cropping** (growing dense cover crops such as mucuna, lablab, or cowpea in the off-season to protect the soil surface from raindrop impact and maintain soil organic matter); **mulching** (covering the soil surface with crop residues, grass, or other materials to absorb raindrop impact, maintain surface roughness, reduce runoff velocity, and conserve moisture); **reduced and minimum tillage** (leaving crop residues on the surface rather than incorporating them, reducing the number of tillage passes, and maintaining soil aggregate stability); and **strip cropping** (alternating strips of erosion-resistant crops such as grasses with strips of erosion-susceptible crops such as maize on slopes).

Contour farming is the practice of conducting all tillage and planting operations along the contour (across the slope) rather than up and down it, creating small ridges and furrows that intercept runoff and increase infiltration time. It is highly effective on gentle to moderate slopes but requires careful layout using a hand level or A-frame. Tied ridging is a modification of the standard ridging practice in which cross-ties are made at regular intervals along the furrows, creating a series of small basins that trap runoff and prevent it from flowing along the furrow down the slope. It is particularly effective for increasing water storage in semi-arid and sub-humid areas with erratic rainfall, and is widely practised in northern Nigeria. These agronomic measures are generally low-cost and can be adopted by smallholder farmers without specialist equipment.

Fill in the blank: ________ farming involves conducting tillage and planting operations along the contour of the slope rather than up and down it, creating ridges that intercept runoff and increase infiltration.

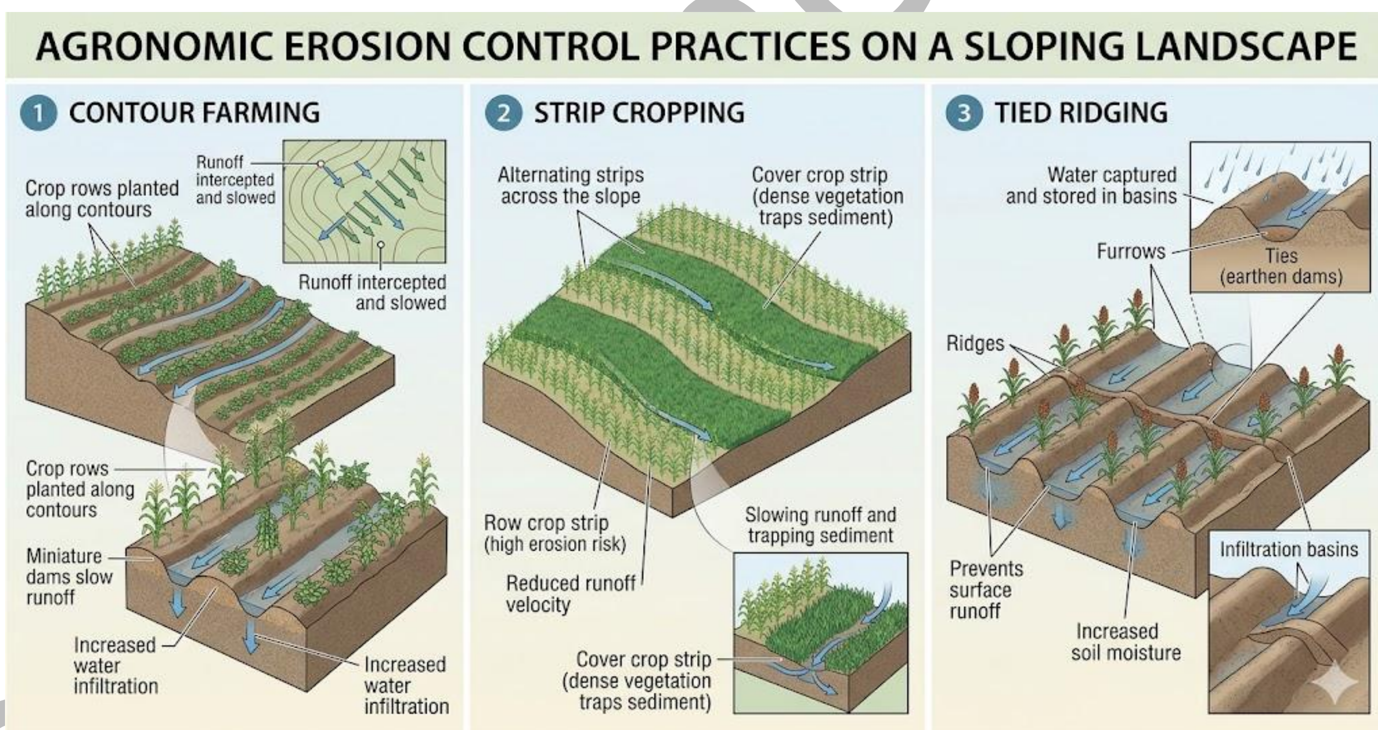

Figure 5.6: Diagram showing contour farming, strip cropping, and tied ridging as agronomic erosion control measures on a sloped landscape

5.3.2 Mechanical and physical conservation structures

Terracing is the construction of level or near-level step-like platforms on hillsides to reduce the effective slope length, slow runoff, and allow water to infiltrate. Bench terraces (horizontal level platforms cut into the hillside) are the most effective but most expensive to construct and maintain; they are appropriate for very steep slopes under intensive cultivation. Broad-base terraces (wide, gently sloping earthen embankments) can be constructed by machinery on gentler slopes and are used on commercial farms. Hillside ditches (graded channels running across the slope at a slight gradient) intercept runoff from above and divert it safely to a waterway at the field edge.

Grass waterways are broad, shallow, grass-covered channels that convey concentrated runoff from the field safely to the drainage outlet without causing gully erosion. They are established by shaping a natural drainage depression into a stable channel and seeding it with a dense, erosion-resistant grass (Rhodes grass, Guinea grass, or vetiver). Check dams are small structures built across existing gullies or drainage channels using stone, earth, or brushwood to slow runoff velocity, trap sediment, and allow gradual revegetation of the gully floor. Gabions (wire baskets filled with stone) are commonly used as check dams in Nigerian gully rehabilitation programmes. The selection and design of physical conservation structures requires site assessment of slope gradient, drainage area, soil type, and expected runoff volumes.

Fill in the blank: Grass ________ are broad, shallow, grass-covered channels that convey concentrated surface runoff safely from the field to a drainage outlet, preventing gully formation in natural drainage depressions.

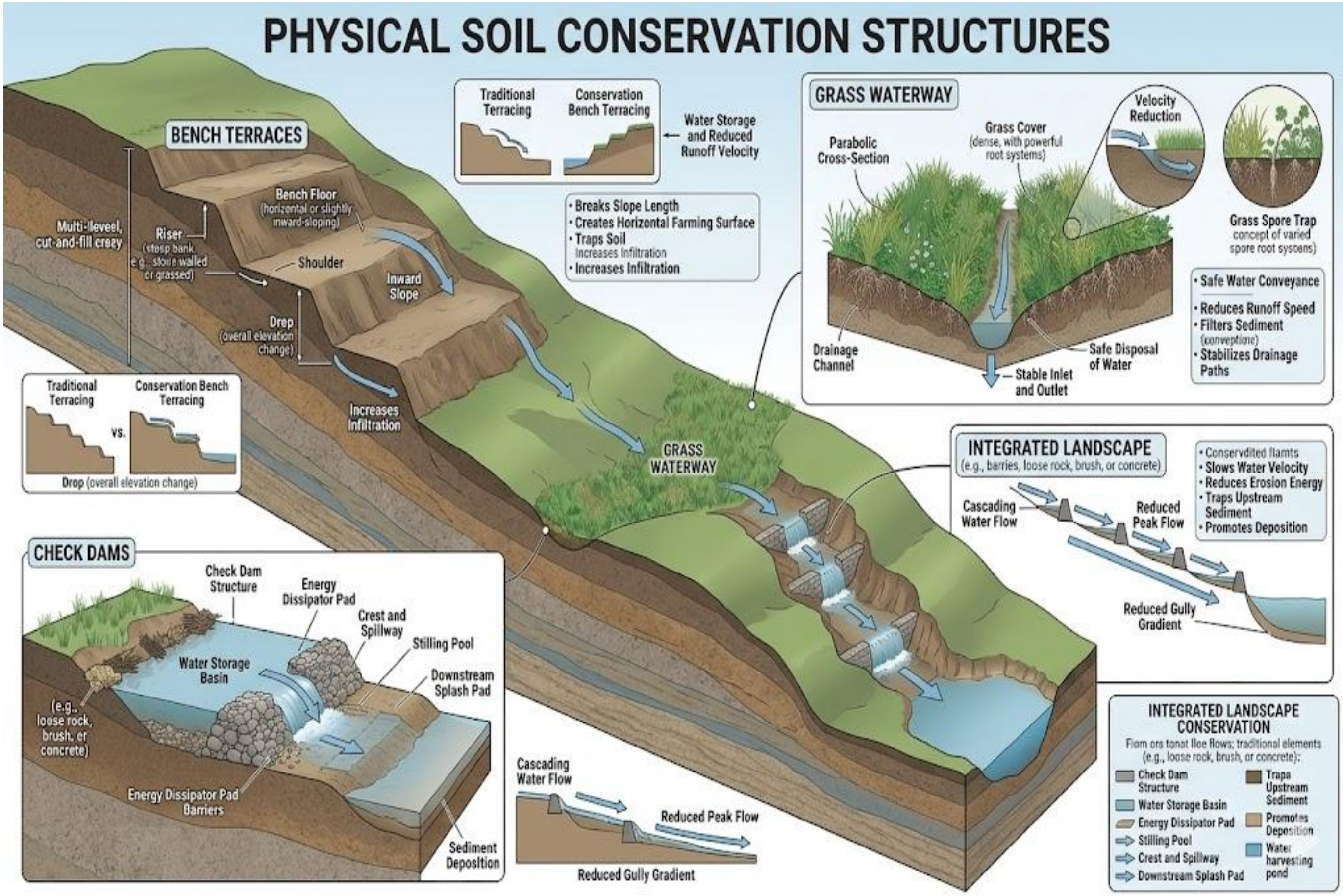

Figure 5.7: Diagram showing bench terraces, grass waterways, and check dams as physical soil conservation structures on a hillside

5.3.3 Agroforestry and integrated land management

Agroforestry is the integration of trees and shrubs with crops and livestock on the same piece of land, combining the benefits of both agricultural and forestry systems. In the context of soil conservation, trees and shrubs contribute in several ways: deep root systems anchor the soil and extract nutrients from subsoil layers inaccessible to annual crops; leaf litter inputs maintain or build soil organic matter; the canopy intercepts rainfall, reducing raindrop erosivity at the ground surface; tree roots create continuous macropores that improve water infiltration; and nitrogen-fixing trees (Faidherbia albida, Gliricidia sepium, Leucaena leucocephala) supply nitrogen to associated crops through leaf litter and pruning material.

Specific agroforestry systems relevant to Nigerian soil conservation include: Faidherbia albida parkland agroforestry (a traditional system of the West African Sahel in which this nitrogen-fixing tree is retained on cropland; the tree drops its leaves at the start of the rainy season, providing natural mulch and green manure when crops need it most); alley cropping (rows of nitrogen-fixing shrubs such as Leucaena or Gliricidia are planted on contours 4 to 8 m apart, with food crops grown in the alleys between; the shrubs are pruned and the biomass applied as mulch and green manure); and windbreaks (linear plantings of trees across the direction of prevailing winds to reduce wind erosion in the semi-arid north). Agroforestry combines multiple benefits including erosion control, soil fertility improvement, carbon sequestration, and livelihood diversification, making it one of the most effective integrated land management strategies for sustainable agriculture in Nigeria.

Fill in the blank: In alley ________, rows of nitrogen-fixing shrubs are planted on contours with food crops grown in the spaces between; the shrubs are pruned and the biomass applied as mulch and green manure for the food crops.

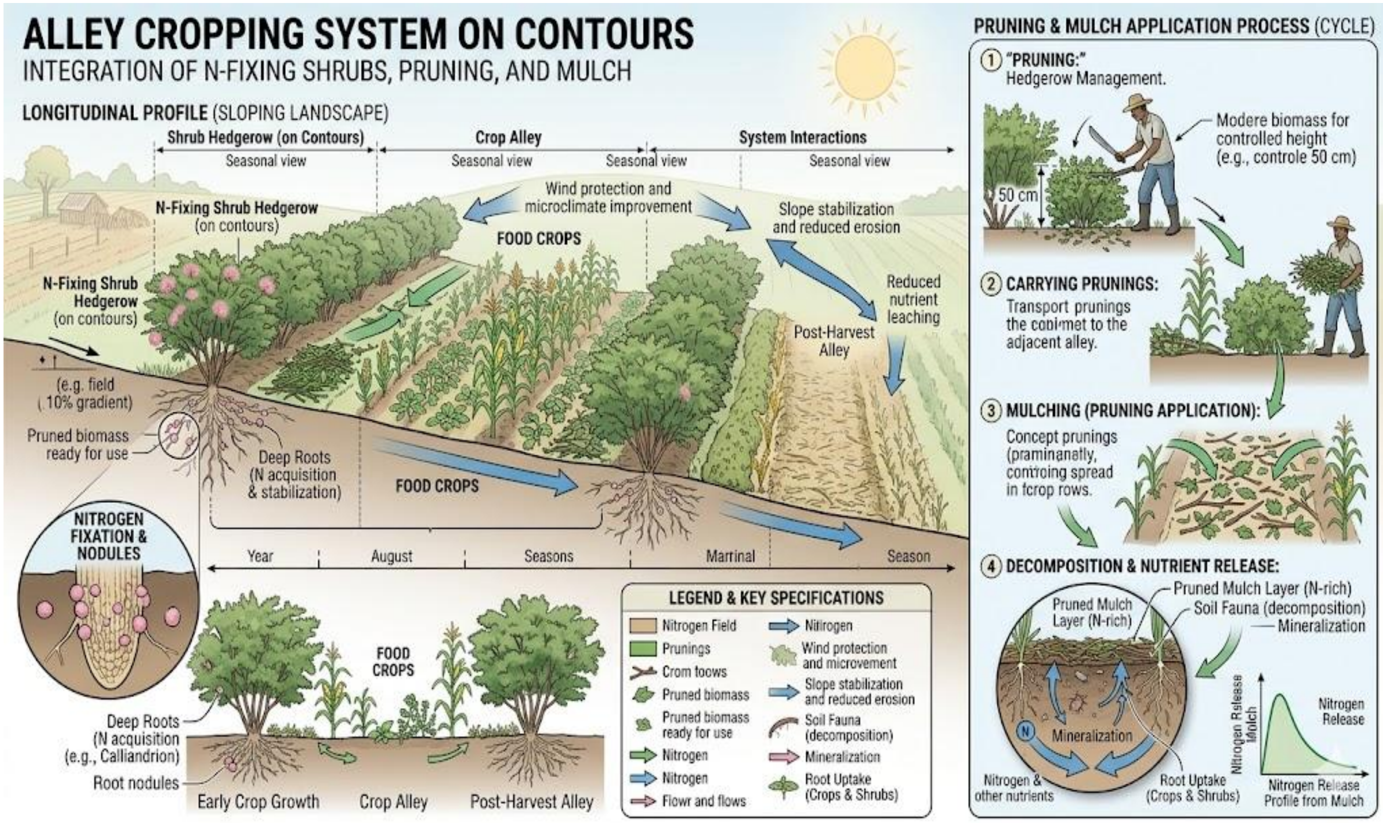

Figure 5.8: Diagram showing alley cropping with nitrogen-fixing shrubs on contours and food crops in the alleys between

Pilot questions 5.3

1. Explain how cover cropping reduces soil erosion.
2. Describe contour farming and explain why all operations should be conducted along the contour rather than up and down the slope.
3. Explain the purpose of a grass waterway in a soil conservation plan.
4. Explain what a check dam is and describe one material used in check dam construction in Nigeria.
5. Describe two ways in which trees in an agroforestry system contribute to soil conservation.

5.4 Sustainable Soil Management

5.4.1 Principles of sustainable soil management

Sustainable soil management is the use of soils in ways that maintain or improve soil health and productivity for future generations while meeting present needs. It rests on five core principles. **Minimise soil disturbance**: excessive tillage destroys aggregate structure, accelerates organic matter oxidation, and increases erosion risk; minimum tillage or no-till systems protect surface aggregates and maintain biological activity. **Maintain permanent soil cover**: bare soil is exposed to raindrop impact, surface sealing, desiccation, and erosion; cover crops, mulches, and retained crop residues protect the surface throughout the year. **Maintain plant diversity**: diverse rotations and intercropping systems support diverse soil biological communities, reduce pest and disease buildup, and diversify organic matter inputs.

The remaining two principles are: replenish organic matter continuously through regular additions of manure, compost, crop residues, and cover crop biomass, recognising that tropical soils decompose organic matter rapidly and require large and frequent inputs to maintain adequate organic matter levels; and keep living roots in the soil as long as possible throughout the year, because growing roots exude sugars and amino acids that feed soil microorganisms and sustain biological activity even outside the main cropping season. These five principles, promoted by the Food and Agriculture Organization as Conservation Agriculture and Sustainable Land Management, represent the current best-practice framework for soil management in tropical smallholder systems such as those dominant in Nigeria.

Fill in the blank: The five principles of sustainable soil management include minimising soil disturbance, maintaining permanent soil ________, maintaining plant diversity, replenishing organic matter, and keeping living roots in the soil year-round.

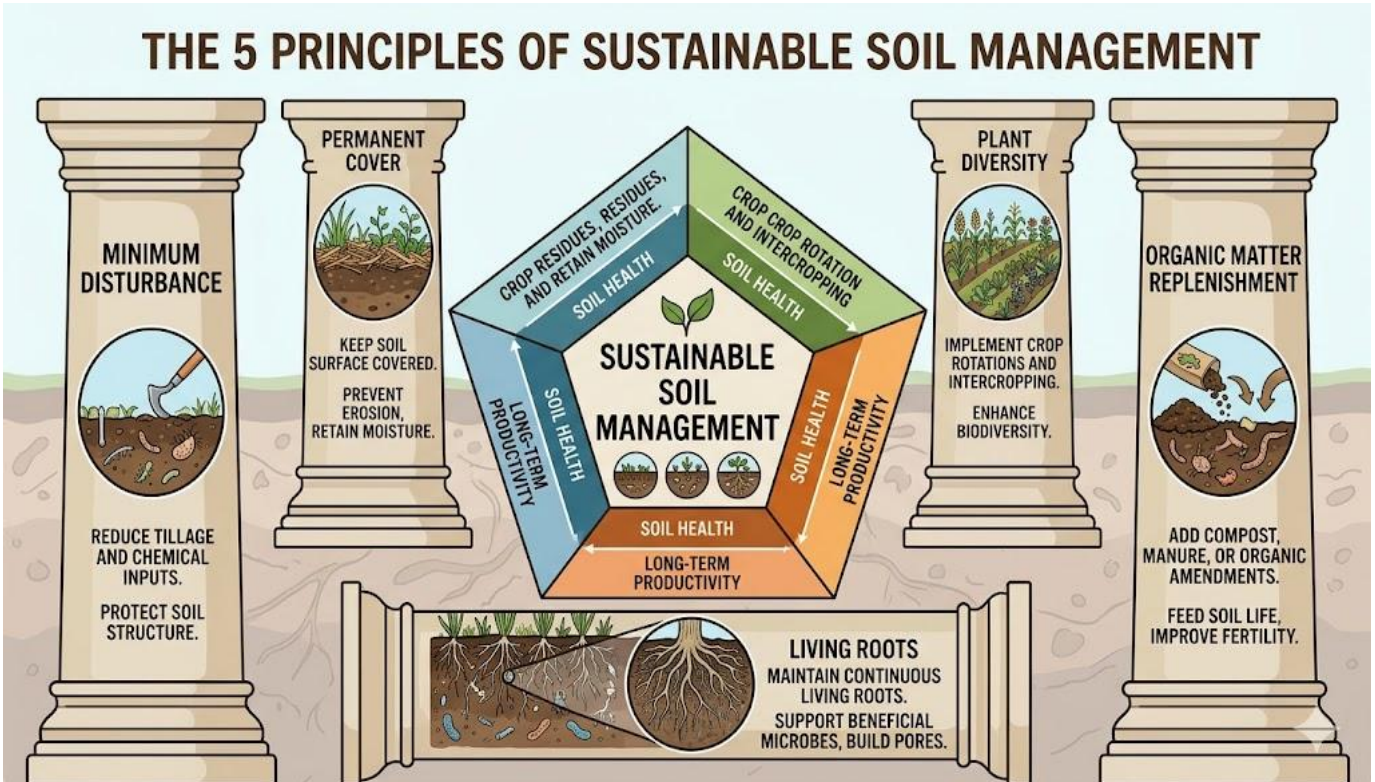

Figure 5.9: Diagram showing the five principles of sustainable soil management and their interactions

5.4.2 Organic matter management and soil health indicators

Organic matter management is the central operational challenge of sustainable soil management in Nigerian agriculture. The organic matter content of cultivated savanna soils has declined from 2 to 3 per cent under natural vegetation to 0.5 to 1.5 per cent under continuous cultivation, with severe consequences for soil fertility, structure, and biological activity. Restoring and maintaining organic matter requires: integrating livestock into the farming system so that manure is returned to cropland; making and applying compost from crop residues, household waste, and manure; retaining crop residues on the field after harvest rather than burning or removing them; growing nitrogen-fixing cover crops in the off-season to add biomass; and integrating trees that produce leaf litter and prunings. On small farms, all available organic materials must be managed carefully to build the organic matter that sustains productivity.

Soil health is assessed using a combination of physical, chemical, and biological indicators that collectively describe the capacity of the soil to function as a productive, sustainable system. Key physical indicators include: bulk density (a measure of compaction; target below 1.3 g/cm3 for loams), aggregate stability (the resistance of aggregates to breakdown by water or mechanical force), and water infiltration rate. Key chemical indicators include: soil organic carbon content, pH, CEC, and nutrient supply capacity. Key biological indicators include: microbial biomass carbon (the mass of living microbial biomass per unit of soil), soil respiration rate, and earthworm counts. Regular monitoring of soil health indicators allows early detection of degradation trends before they become irreversible, enabling timely management interventions.

Fill in the blank: Soil ________ density is a key physical indicator of soil compaction; values above 1.3 g/cm3 in loamy soils indicate compaction that restricts root penetration, drainage, and aeration.

Indicator Type	**Indicator**	**Target Range (Tropical Soils)**	**Measurement Method**
Physical	Bulk density	1.1 – 1.4 g/cm^3	Core sampling, oven-dry method
	Aggregate stability	> 60% stable aggregates	Wet sieving test
	Infiltration rate	5 – 15 cm/hr	Double-ring infiltrometer
Chemical	Soil pH	5.5 – 7.0	pH meter or indicator strips
	Organic carbon	> 1.5%	Walkley-Black or dry combustion
	CEC (Cation Exchange Capacity)	10 – 25 cmol/kg	Ammonium acetate extraction
	Base saturation	> 50%	Exchangeable bases analysis
Biological	Microbial biomass C	200 – 600 mg/kg	Fumigation-extraction method
	Earthworm count	> 10 per m^2	Field hand-sorting or soil monoliths
	Soil respiration	50 – 150 mg CO_2/kg/day	Alkali absorption or infrared gas analysis

Table 5.1: Key soil health indicators, their target ranges for tropical agricultural soils, and measurement methods

5.4.3 Soil management for climate change adaptation

Climate change poses multiple threats to soil health and agricultural productivity in Nigeria: higher temperatures accelerate organic matter decomposition, reducing organic matter levels and increasing nutrient mineralisation rates (which may initially increase nutrient availability but ultimately deplete organic matter reserves); more intense rainfall events increase runoff and erosion; more frequent and severe droughts reduce soil biological activity, increase salt accumulation through higher evaporation, and cause soil cracking and surface hardening; and sea level rise threatens coastal and delta soils with salinisation and flooding.

Soil management practices that build climate change adaptation in Nigerian agriculture include: increasing soil organic matter (which increases water-holding capacity, reducing vulnerability to drought; increases aggregate stability, reducing erosion from intense rainfall; and buffers soil temperature fluctuations); conservation tillage (which retains surface residue that reduces surface runoff, moderates soil temperature, and maintains infiltration capacity under high-intensity rainfall); agroforestry (which provides shade and wind protection, reduces soil surface temperature, and maintains organic matter inputs even during dry periods when annual crop production fails); and integrated watershed management (which coordinates land use and conservation practices across entire catchments to manage water and sediment at the landscape scale). Healthy soils also contribute to climate change mitigation by sequestering atmospheric carbon in stable organic matter, making soil management a dual adaptation and mitigation strategy.

Fill in the blank: Increasing soil organic matter is the most important single soil management strategy for climate change adaptation because it improves water-________ capacity, aggregate stability, and buffering of temperature fluctuations.

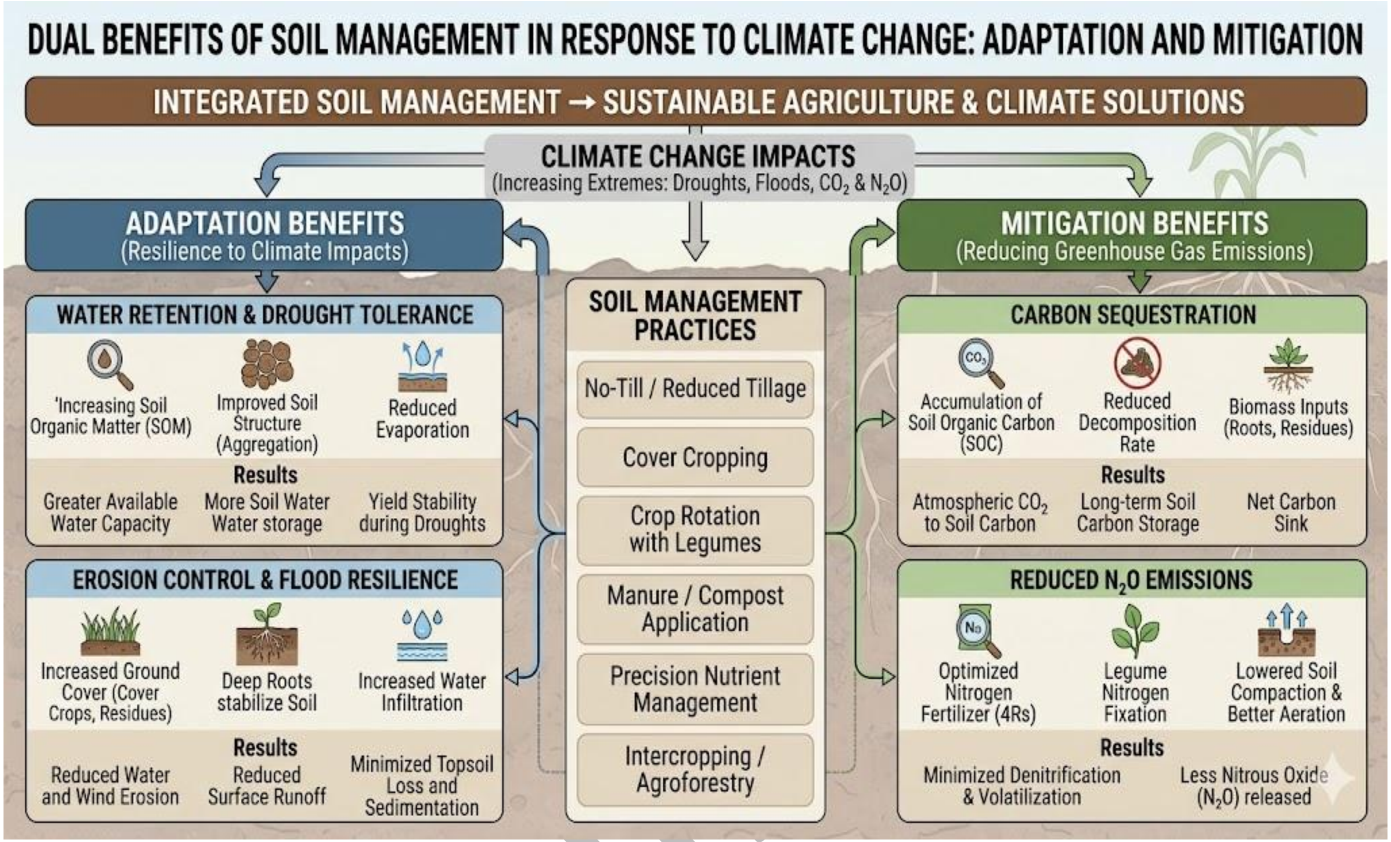

Figure 5.10: Diagram showing how soil management practices contribute to both climate change adaptation and mitigation

Pilot questions 5.4

1. State the five principles of sustainable soil management.
2. Explain why tropical soils need larger and more frequent organic matter additions than temperate soils.
3. Name three physical and two chemical soil health indicators.
4. Describe two ways in which climate change threatens soil health in Nigeria.
5. Explain how increasing soil organic matter contributes to both climate change adaptation and mitigation.

Series Summary

This final Series has addressed soil degradation, conservation, and sustainable management, completing the introduction to soil science by connecting the fundamental knowledge of the preceding series to the applied challenges of sustaining soil productivity in Nigeria. We began with soil erosion, classifying the types of water erosion (splash, sheet, rill, gully) and wind erosion, explaining the five USLE factors that control erosion rate, and describing the on-site (fertility and rooting depth loss) and off-site (sedimentation and eutrophication) consequences, and the methods of erosion assessment and measurement. We then covered other forms of degradation: compaction and structural degradation (tillage pan, surface sealing), salinisation and sodification (primary and secondary, reclamation with drainage and gypsum), and soil pollution (agrochemicals, heavy metals, petroleum hydrocarbons, and remediation strategies).

Following that, we examined soil conservation measures, contrasting agronomic and vegetative practices (cover cropping, mulching, minimum tillage, strip cropping, contour farming, tied ridging) with mechanical structures (terracing, grass waterways, check dams, gabions) and integrating them within agroforestry systems (Faidherbia parklands, alley cropping, windbreaks) that simultaneously address erosion control, soil fertility, and livelihood diversification. Finally, we introduced the framework of sustainable soil management, stating its five core principles, explaining the central importance of organic matter management for maintaining soil health in tropical conditions, describing physical, chemical, and biological soil health indicators, and establishing how appropriate soil management contributes to both adaptation and mitigation in the context of climate change. By completing this Series and the course as a whole, you should now be able to achieve all nine Series Learning Outcomes (SLO 5.1 to SLO 5.9) and all six course learning outcomes.

Glossary of Terms

- **Alley cropping:** an agroforestry system in which rows of nitrogen-fixing shrubs or trees are planted on contours with food crops grown in the alleys between; shrubs are pruned and biomass applied as mulch and green manure.

- **Bench terrace:** a level or near-level step-like platform cut into a hillside to reduce slope length, slow runoff, and allow infiltration; the most effective but most expensive terracing type for steep slopes.
- **Bioremediation:** the use of microorganisms (bacteria, fungi) to degrade or detoxify organic contaminants in polluted soil; effective for petroleum hydrocarbons and some pesticides.
- **Bulk density:** the mass of oven-dry soil per unit volume including pore space, expressed in g/cm3; increases with compaction; values above 1.3 g/cm3 in loamy soils indicate restrictive compaction.
- **Check dam:** a small structure built across a gully or drainage channel to slow runoff, trap sediment, and allow gradual revegetation; commonly constructed from stone, brushwood, or gabion baskets in Nigeria.
- **Conservation agriculture:** a farming system based on the three principles promoted by FAO: minimum mechanical soil disturbance, permanent soil cover, and crop rotations or associations.
- **Contour farming:** the practice of conducting all tillage and planting operations across the slope (along the contour) rather than up and down it, creating ridges that intercept runoff and increase infiltration time.
- **Cover crop:** a crop grown primarily to protect and improve the soil between main crop seasons; provides surface cover, adds organic matter, suppresses weeds, and may fix nitrogen if leguminous.
- **Exchangeable sodium percentage (ESP):** the percentage of the CEC occupied by sodium ions (Na^+); ESP above 15 per cent defines a sodic soil with poor physical properties.
- **Gabion:** a wire basket filled with stones, used as a check dam or erosion control structure in stream channels and gullies.
- **Grass waterway:** a broad, shallow, grass-covered channel that conveys concentrated surface runoff safely from a field to a drainage outlet without causing gully erosion.
- **Gully erosion:** severe water erosion in which concentrated runoff carves large, permanent channels that cannot be obliterated by normal tillage and represent a major land degradation problem in south-eastern Nigeria.

- **Microbial biomass carbon:** the mass of carbon contained in living soil microorganisms per unit mass of soil; a sensitive biological indicator of soil health and organic matter turnover.
- **Phytoremediation:** the use of hyperaccumulator plants to absorb and concentrate heavy metals from contaminated soil into their above-ground biomass, which is then harvested and removed.
- **Primary salinisation:** natural accumulation of soluble salts in the soil in arid and semi-arid areas, driven by upward capillary movement of saline groundwater and surface evaporation.
- **Rill erosion:** water erosion in which concentrated runoff cuts small channels across the slope that are large enough to be visible but can still be obliterated by tillage.
- **Secondary salinisation:** human-induced accumulation of salts in irrigated soils, caused by applying irrigation water without adequate drainage, raising the water table and bringing dissolved salts to the surface.
- **Sheet erosion:** the thin, uniform removal of topsoil by shallow surface flow across the whole slope; difficult to observe directly but causes significant cumulative topsoil loss over time.
- **Sodification:** the accumulation of sodium ions on soil exchange sites, causing clay deflocculation, structural collapse, and very poor physical properties.
- **Soil health:** the continued capacity of a soil to function as a vital living ecosystem that sustains plants, animals, and humans, assessed through physical, chemical, and biological indicators.
- **Splash erosion:** the detachment of soil particles by raindrop impact, the first stage of water erosion; creates a surface seal that reduces infiltration.
- **Strip cropping:** the alternation of strips of erosion-resistant crops (grasses, dense legumes) with strips of erosion-susceptible crops across or along the contour of a slope.
- **Terracing:** the construction of level or near-level step-like platforms on hillsides to reduce effective slope length and allow runoff to infiltrate rather than flow downslope.
- **Tied ridging:** a modified ridging practice in which cross-ties are built at regular intervals along furrows to create small water-storage basins that trap runoff and increase infiltration.
- **Tillage pan (plough pan):** a dense, compacted layer just below normal ploughing depth, created by repeated smearing action of the plough bottom on moist soil; restricts root penetration and drainage.

- **Universal Soil Loss Equation (USLE):** an empirical equation $A = R \times K \times L \times S \times C \times P$ used to predict annual soil loss from sheet and rill erosion; the most widely used tool for erosion risk assessment and conservation planning.
- **Windbreak:** a linear planting of trees or shrubs across the direction of prevailing wind to reduce wind speed and wind erosion; used widely in the semi-arid northern Nigeria to protect sandy soils from harmattan erosion.

Concept Check Questions [Series 5]

Objective Questions

1. In the USLE, the letter A represents predicted soil ________ per unit area per year. (Linked to SLO 5.3)
2. A tillage ________ is the dense compacted layer that forms just below the depth of repeated ploughing, restricting root penetration and drainage. (Linked to SLO 5.4)
3. Reclamation of sodic soils requires addition of ________ to replace sodium on exchange sites with calcium. (Linked to SLO 5.4)
4. ________ farming involves conducting all field operations along the contour to intercept runoff and increase infiltration. (Linked to SLO 5.5)
5. Soil bulk density values above ________ g/cm3 in loamy soils indicate compaction that restricts root growth. (Linked to SLO 5.9)

Short-Answer Questions

1. Name and briefly describe the four types of water erosion in order of increasing severity. (Linked to SLO 5.1)
2. State three on-site and two off-site consequences of soil erosion. (Linked to SLO 5.2)
3. Explain the difference between soil salinisation and soil sodification. (Linked to SLO 5.4)
4. Describe two agronomic conservation measures and explain how each reduces erosion. (Linked to SLO 5.5)
5. State the five principles of sustainable soil management. (Linked to SLO 5.8)

Long-Answer Questions

1. Analyse soil erosion as the most important form of soil degradation in Nigeria, describing the types and causes, the factors incorporated in the USLE, the on-site and off-site consequences, and the methods used to assess and measure erosion in the field. (Linked to SLOs 5.1, 5.2, 5.3)
2. Discuss the full range of soil conservation and erosion control measures available to Nigerian farmers, covering agronomic and vegetative practices, mechanical structures, and agroforestry systems, and explaining how these can be combined in an integrated conservation plan for a sloping Nigerian farm. (Linked to SLOs 5.5, 5.6, 5.7)
3. Evaluate sustainable soil management as the framework for addressing soil degradation and climate change adaptation in Nigeria, explaining the five principles, describing the importance of organic matter management, identifying key soil health indicators, and explaining how appropriate soil management contributes to both adaptation and mitigation. (Linked to SLOs 5.8, 5.9)

Answers to Concept Check Questions [Series 5]

Objective Questions

1. Loss.
2. Pan.
3. Gypsum.
4. Contour.
5. 1.3.

Short-Answer Questions

1. Splash erosion: raindrop impact detaches soil particles and creates a surface seal reducing infiltration. Sheet erosion: thin uniform removal of topsoil by shallow surface flow; difficult to observe but causes significant cumulative loss. Rill erosion: concentrated runoff cuts small channels that can still be removed by tillage. Gully erosion: large permanent channels that cannot be removed by tillage; the most severe form causing major land degradation.
2. On-site: loss of fertile topsoil reducing crop yields; reduced effective rooting depth; destruction of soil structure increasing runoff and further erosion. Off-site: sedimentation of streams, reservoirs, and irrigation canals reducing their capacity; transport of adsorbed phosphorus, organic matter, and pesticides causing eutrophication and water quality degradation.
3. Soil salinisation is the accumulation of soluble salts (sodium chloride, magnesium sulphate) in the soil to concentrations that inhibit plant growth through osmotic stress; it is remediated by drainage and fresh water leaching to remove salts below the root zone. Soil sodification is the accumulation of sodium ions on soil exchange sites (high exchangeable sodium percentage) causing clay deflocculation, structural collapse, very low infiltration, and poor physical properties; it additionally requires application of gypsum to replace sodium with calcium before leaching is effective.
4. Any two: cover cropping reduces erosion by protecting the soil surface from raindrop impact throughout the year, maintaining surface roughness that slows runoff velocity, and adding organic matter that improves aggregate stability; mulching reduces erosion by absorbing raindrop kinetic energy at the soil surface (preventing splash detachment), maintaining surface roughness, slowing runoff velocity, and conserving soil moisture which reduces the erodibility of the soil.

5. The five principles are: (1) minimise soil disturbance by reducing tillage intensity; (2) maintain permanent soil cover with crop residues, mulch, or cover crops; (3) maintain plant diversity through rotations and intercropping; (4) replenish organic matter continuously through manure, compost, and cover crops; (5) keep living roots in the soil as long as possible throughout the year.

Long-Answer Questions

1. Basic response: Water erosion types: splash (raindrop impact, surface sealing), sheet (thin uniform topsoil removal), rill (small concentrated channels, tillable), gully (large permanent channels, most severe). Wind erosion: suspension, saltation, surface creep; severe in semi-arid north. USLE factors: R (rainfall erosivity, high in Nigerian storms with large drops), K (soil erodibility, texture and organic matter), L and S (slope length and steepness), C (cover and management factor), P (support practice). On-site: topsoil loss, reduced fertility, reduced rooting depth, self-reinforcing erosion cycle. Off-site: reservoir sedimentation, flood risk, eutrophication from phosphorus transport. Assessment: qualitative (exposed roots, pedestals, rill patterns), quantitative (erosion pins, sediment traps from standard plots), USLE predictive model.
2. Value-added response: The most important insight from studying erosion in the context of Nigerian soils is that the most severely eroded zones are not the steepest slopes but the moderately sloped cultivated uplands where Alfisol A horizons are thin (20 to 30 cm) over plinthite B horizons. Even slight erosion of 2 to 5 cm per year on these soils progressively exposes the plinthite layer, which on drying hardens irreversibly into ironstone, creating a permanently infertile surface that cannot be rehabilitated by any practical management. The economic and food security consequences of losing these soils are therefore catastrophic and irreversible, making erosion prevention the highest-priority soil management investment in the Nigerian Guinea savanna.
3. Basic response: Agronomic measures: cover crops (protect surface from raindrop impact, add organic matter); mulching (absorbs raindrop energy, slows runoff); minimum tillage (maintains aggregates and residue cover); strip cropping (alternating erosion-resistant strips); contour farming (cross-slope operations intercept runoff); tied ridging (small basins trap runoff, increase infiltration). Mechanical structures: bench terraces (steep slopes, expensive, effective); broad-base terraces (machinery, commercial farms); grass waterways (safe conveyance of concentrated runoff); check dams and gabions (gully rehabilitation). Agroforestry: Faidherbia parklands (natural mulch and N at start of rains); alley cropping

(Leucaena or Gliricidia on contours, prunings as mulch and green manure); windbreaks (semi-arid north, wind erosion control). Integrated plan: combine agronomic measures on fields with mechanical structures on drainage lines and agroforestry on boundaries and steeper slopes.

4. Value-added response: The most transformative single practice for a sloping Nigerian smallholder farm is the combination of contour ridging and tied ridging with a leguminous cover crop in the off-season. Contour ridging alone reduces runoff by 40 to 60 per cent on typical Guinea savanna slopes; adding cross-ties to create tied ridging further reduces runoff while increasing water storage for the early dry period when crops are still maturing; the off-season legume cover (mucuna or lablab) protects the soil surface during the most erosive wet season storms if grown as an understory, adds 80 to 120 kg N/ha through fixation, and provides 3 to 5 tonnes/ha of mulch biomass for the following season. This combination can be adopted by smallholder farmers with a hand hoe and costs almost nothing beyond the seed investment, yet addresses erosion, nitrogen, water, and organic matter deficits simultaneously.
5. Basic response: Five principles: minimum disturbance, permanent cover, plant diversity, replenish organic matter, living roots year-round. Organic matter management: savanna soils declined from 2 to 3 per cent to 0.5 to 1.5 per cent under continuous cultivation; restore through livestock integration (manure return), composting, residue retention, cover crops, and agroforestry. Soil health indicators: physical (bulk density less than 1.3 g/cm^3, aggregate stability, infiltration rate); chemical (organic carbon, pH, CEC, nutrient levels); biological (microbial biomass carbon, soil respiration, earthworm counts). Climate adaptation: higher temperatures accelerate decomposition; intense rainfall increases erosion; drought increases salinity. Organic matter management: increases water-holding capacity (drought resilience); improves aggregate stability (intense rainfall resilience); conservation tillage and agroforestry moderate surface temperature. Mitigation: stable organic matter sequesters atmospheric carbon; healthy soils reduce N_2O emissions from denitrification.
6. Value-added response: The most important reframing that soil science can offer to Nigerian agricultural development policy is shifting from the question "how much fertiliser do we need?" to the question "how do we manage the soil so that less fertiliser is needed?" A soil with 2 per cent organic carbon, stable aggregate structure, abundant earthworms and mycorrhizal fungi, and an appropriate pH is a soil that converts 50 to 60 per cent of applied nitrogen into crop yield; the same crop on a degraded soil with 0.5 per cent organic carbon, poor structure, and pH of 4.8 converts only 20 to 30 per cent of applied nitrogen. The

difference is not the fertiliser but the soil. Teaching students to see soil health as the primary investment and fertiliser as the complement rather than the solution is the most important intellectual shift that this course can achieve.

Answers to Pilot Questions [Series 5]

Part 5.1: Soil Erosion

1. Splash erosion: raindrop impact detaches individual soil particles from the aggregate surface, disrupts surface aggregates, and washes fine particles into pores, creating a surface seal that reduces infiltration. Sheet erosion: thin, uniform removal of topsoil by shallow surface flow across the whole slope; not visible as channels and therefore easily overlooked until significant fertility loss has occurred. Rill erosion: concentrated runoff cuts small channels (rills) across the slope that are visible but still small enough to be obliterated by the next tillage operation. Gully erosion: concentrated runoff carves large, deep permanent channels that cannot be removed by any tillage, represent the most visible and damaging form of erosion, and cause direct land loss.
2. Rainfall erosivity (R) is the kinetic energy of rainfall, which determines its capacity to detach soil particles and generate runoff; it is proportional to the square of rainfall intensity; Nigerian tropical rainfall has high erosivity because West African rainstorms are typically convective (short, intense bursts) with large raindrop sizes that deliver very high kinetic energy per unit of rainfall; a single intense storm of 50 mm in one hour can deliver more erosive energy than several weeks of gentle rainfall of the same total volume.
3. Any three: loss of the organic-matter-rich, biologically active A horizon that provides the most fertility and the best physical properties for crop growth; reduced rooting depth available to crops, restricting access to water and subsoil nutrients; destruction of soil aggregate structure increasing runoff and susceptibility to further erosion; exposure of infertile, possibly plinthite-containing B horizon that is harder to till and less productive.
4. Any two: sedimentation of streams, rivers, and reservoirs as transported soil material is deposited, reducing channel capacity, increasing flood risk, and shortening the operational life of dams and irrigation infrastructure; transport of adsorbed phosphorus, organic matter, and pesticides from the eroded topsoil into water bodies, causing eutrophication (excess

nutrient enrichment leading to algal blooms, oxygen depletion, and fish kills) and water quality degradation that increases treatment costs for drinking water.

5. A (predicted annual soil loss per unit area): the output variable in tonnes per hectare per year. R (rainfall erosivity factor): reflects the kinetic energy of rainfall and its capacity to detach soil. K (soil erodibility factor): reflects how easily the soil particles are detached and transported, determined by texture, organic matter, aggregate stability, and permeability. L (slope length factor): longer slopes accumulate more runoff and have higher erosion. S (slope steepness factor): steeper slopes have faster runoff and greater erosive capacity. C (cover and management factor): reflects the effect of vegetative cover and crop management on erosion protection. P (support practice factor): reflects the effect of conservation practices such as contouring and terracing.

Part 5.2: Other Forms of Soil Degradation

1. Soil compaction is the reduction in soil pore space and increase in bulk density caused by mechanical pressure from traffic or tillage on wet soil; it reduces crop production by: reducing water infiltration (causing surface ponding, runoff, and drought stress during dry periods); decreasing aeration (impairing root respiration and microbial nutrient cycling); increasing mechanical resistance to root penetration (restricting root access to water and nutrients in the subsoil); and reducing the volume of soil available to roots, reducing the total plant-available water supply.
2. A tillage pan is a dense compacted layer formed just below the depth of repeated ploughing, created by the smearing and compaction action of the plough bottom on moist soil over successive seasons; it has much higher bulk density and much lower porosity than the overlying cultivated layer; its effects on drainage: percolating water is impeded at the tillage pan boundary, causing the topsoil layer to become waterlogged after rainfall even if the subsoil below the pan is well-drained; effect on root development: most crop roots cannot penetrate the dense pan layer, restricting them to the thin surface cultivated layer and limiting access to subsoil water and nutrients.
3. Soil salinisation is the accumulation of soluble salts (sodium chloride, magnesium sulphate, calcium chloride) in the soil to concentrations that inhibit plant growth through osmotic stress (plants cannot take up water when the soil solution is more concentrated than the cell fluid); soils may appear white from salt crystals at the surface; primary salinisation occurs naturally in arid areas, secondary salinisation is induced by poor irrigation management. Soil sodification is the accumulation of sodium ions (Na^+) specifically on the CEC exchange

sites, displacing calcium and magnesium; it causes clay deflocculation (clay particles separate and clog pores), structural collapse, very poor infiltration, and extremely hard surface crust when dry; it may occur independently of high total salt concentration.

4. Secondary salinisation develops when irrigated fields lack adequate drainage: irrigation water always contains some dissolved salts; when applied in excess of crop and drainage requirements, water accumulates in the subsoil, raising the water table; as the raised water table approaches the surface, capillary forces draw saline water upward to the root zone and surface; at the surface, water evaporates and salts are deposited as crystals; repeated irrigation without adequate drainage progressively concentrates salts until concentrations become phytotoxic; the problem is most severe in flat, fine-textured soils with shallow impermeable layers that prevent natural downward drainage.
5. Any two sources with remediation: agrochemical misuse (persistent pesticides such as organochlorines accumulate in the food chain); remediation by bioremediation using pesticide-degrading microorganism populations enriched in the soil. Heavy metal contamination from artisanal gold mining in Zamfara state (cadmium, lead, arsenic); remediation by phytoremediation using metal-accumulating plants such as sunflower or thlaspi to extract metals from the soil, or by chemical immobilisation using lime to raise pH and reduce metal solubility.

Part 5.3: Soil Conservation and Erosion Control

1. Cover crops protect soil from erosion in several ways: the canopy of the cover crop intercepts raindrops before they reach the soil surface, breaking their fall and greatly reducing the kinetic energy with which they impact the soil (protecting aggregates from splash detachment); roots of cover crops hold the soil in place and create channels that improve infiltration, reducing surface runoff volume and velocity; the decomposing biomass of the cover crop adds organic matter that improves aggregate stability, making soil particles more resistant to detachment; and the dense stand of cover crop slows surface runoff flow, giving water more time to infiltrate rather than running off the slope.
2. Contour farming involves conducting all tillage and planting operations across the slope at a constant elevation rather than up and down the slope; when tillage is done up and down the slope, the furrows become channels that direct surface runoff downslope, accelerating its velocity and erosive power; when tillage is done along the contour, the ridges and furrows created act as small barriers that interrupt the downslope flow of runoff, forcing it to slow and infiltrate rather than continuing downslope; this can reduce runoff volume by 30 to 50 per

cent and erosion by even more on moderate slopes, and it must be laid out carefully using a level or A-frame to ensure that ridges truly follow the contour and do not divert water to one end of the field.

3. A grass waterway is needed in a soil conservation plan because contour ridges, terraces, and other structures that intercept runoff must have a safe outlet to discharge the water they collect; without a stable outlet, concentrated runoff breaks through ridges or flows at the ends of terraces and cuts gullies in unprotected soil; a grass waterway is designed as a broad, shallow channel in a natural drainage depression, seeded with dense erosion-resistant grass, that conducts this concentrated runoff at low enough velocity (below the critical velocity for that soil) to prevent erosion of the channel itself; it is the essential drainage safety valve of any conservation plan.
4. A check dam is a small structure built across the floor of an existing gully or drainage channel to slow the velocity of runoff flowing through it, trap sediment that accumulates behind the structure, raise the base level of erosion in the channel, and allow gradual revegetation of the gully floor and walls with the accumulated sediment and moisture; one material commonly used in Nigeria: stone (dry stone check dams are built by stacking local quarry stone or field stone across the gully floor and are effective, inexpensive, and durable if correctly designed with adequate overflow spillways).
5. Any two: deep root systems of trees anchor the soil and extend into subsoil layers where they create continuous macropores that improve water infiltration, reducing surface runoff that causes erosion; the canopy of trees intercepts rainfall, breaking the fall of raindrops before they reach the soil surface, reducing their kinetic energy and therefore their ability to detach soil particles and create surface seals.

Part 5.4: Sustainable Soil Management

1. The five principles are: (1) minimise soil disturbance (reduce tillage to protect aggregate structure and organic matter); (2) maintain permanent soil cover at all times with residues, mulch, or cover crops; (3) maintain plant diversity through diverse rotations and intercropping to support soil biological communities; (4) replenish organic matter continuously through manure, compost, cover crops, and crop residue retention; (5) keep living roots in the soil as long as possible through the year to sustain microbial activity with root exudates.
2. Tropical soils decompose organic matter much more rapidly than temperate soils because the high temperatures (25 to 35°C) throughout the year support year-round microbial activity at

rates two to four times higher than in temperate climates; a Nigerian savanna soil can decompose the same quantity of organic matter in one to two years that a cool temperate soil would take five to ten years to decompose; this means that the same quantity of organic matter added to a tropical soil produces a much smaller sustained increase in soil organic matter content than in a temperate soil; correspondingly larger and more frequent additions are needed simply to maintain organic matter at its current level, and even larger additions are needed to increase it.

3. Three physical: bulk density (compaction indicator, target below 1.3 g/cm3 for loams), aggregate stability (resistance of aggregates to breakdown by water, target high), water infiltration rate (measure of porosity and structure, target high). Two chemical: soil organic carbon content (target above 1.5 per cent in tropical soils), pH (target appropriate to crop requirements, generally 5.5 to 6.5 for most Nigerian crops).
4. Any two: higher temperatures accelerate soil organic matter decomposition, progressively depleting the organic matter that maintains soil fertility, structure, and water retention, making soils less productive and more vulnerable to further degradation. More intense and erratic rainfall events increase surface runoff and water erosion rates on bare or poorly structured soils, and increase the frequency of extreme droughts that reduce soil biological activity, promote salt accumulation through higher evaporation, and cause soil cracking and hardening that reduce water infiltration in subsequent rainfall events.
5. Adaptation contribution: higher organic matter increases the water-holding capacity of the soil (each 1 per cent increase in organic matter can increase plant-available water by 1 to 4 mm per 10 cm of soil depth), making crops more resilient to drought between rainfall events; organic matter also improves aggregate stability so that soils with higher organic matter better resist the intense erosion caused by high-intensity rainfall events predicted to increase under climate change. Mitigation contribution: stable humus and humin fractions of soil organic matter represent long-term carbon sequestration from the atmosphere; globally, agricultural soils have lost 40 to 90 billion tonnes of carbon through tillage and degradation, representing a large potential sink if soil carbon is rebuilt through sustainable management; healthy soils with good aeration also produce less N2O from denitrification than degraded, compacted, waterlogged soils, further reducing greenhouse gas emissions.

References and Attributions [Series 5]

Textual References (Books and External Sources)

- Morgan, R. P. C. (2005). Soil erosion and conservation (3rd ed.). Blackwell Publishing.
- Lal, R. (1990). Soil erosion in the tropics: Principles and management. McGraw-Hill.
- Brady, N. C., & Weil, R. R. (2016). The nature and properties of soils (15th ed.). Pearson Education.
- Mando, A., Ouattara, B., Sedogo, M., Stroosnijder, L., Ouattara, B., Brussaard, L., & Vanlauwe, B. (2005). Long-term effect of tillage and manure application on soil organic fractions and crop performance under Sudano-Sahelian conditions. Soil and Tillage Research, 80(1-2), 95-101.
- Nair, P. K. R. (1993). An introduction to agroforestry. Kluwer Academic Publishers.
- FAO (Food and Agriculture Organization of the United Nations). (2025). Guidelines for sustainable agriculture. FAO.

Figures, Plates, Tables, and Boxes

- Figure 5.1: Water erosion types progression diagram Attribution: AI generated using prompt "Generate a four-panel diagram showing the progression of water erosion types from splash erosion through sheet, rill, and gully erosion with increasing severity." Suggested OER search string: "water erosion types splash sheet rill gully progression diagram OER".
- Figure 5.2: Erosion on-site and off-site consequences diagram Attribution: AI generated using prompt "Generate a watershed diagram showing on-site erosion effects on upper slopes and off-site sedimentation and water quality effects in the lower watershed." Suggested OER search string: "soil erosion on-site off-site consequences sedimentation watershed OER diagram".
- Figure 5.3: USLE erosion research plot diagram Attribution: AI generated using prompt "Generate a diagram of a standard USLE erosion research plot with 22.1 m length, bordered sides, and sediment collection system at the base." Suggested OER search string: "USLE erosion research plot dimensions sediment collection system OER diagram".
- Figure 5.4: Soil compaction effects diagram Attribution: AI generated using prompt "Generate a cross-section diagram comparing uncompacted soil and compacted soil with tillage pan, showing differences in pore structure, root penetration, and infiltration." Suggested OER search string: "soil compaction effects pore structure root penetration tillage pan OER diagram".
- Figure 5.5: Secondary salinisation diagram Attribution: AI generated using prompt "Generate a cross-section diagram showing secondary salinisation development in an irrigated field with

rising water table, capillary rise, and salt accumulation at the soil surface." Suggested OER search string: "secondary salinisation irrigated soil rising water table capillary salt OER diagram".

- Box 5.1: Soil pollution sources in Nigeria Attribution: AI generated using prompt "Generate a text box listing the main sources of soil pollution in Nigeria including agrochemicals, heavy metals from mining, industrial waste, and petroleum spills with effects on soil and crops." Suggested OER search string: "soil pollution sources Nigeria agrochemicals heavy metals petroleum OER box".
- Figure 5.6: Agronomic erosion control practices diagram Attribution: AI generated using prompt "Generate a three-panel diagram showing contour farming, strip cropping, and tied ridging as agronomic erosion control practices on a sloping landscape." Suggested OER search string: "contour farming strip cropping tied ridging erosion control OER diagram".
- Figure 5.7: Physical soil conservation structures diagram Attribution: AI generated using prompt "Generate a diagram showing bench terraces on a steep slope, a grass waterway in a drainage channel, and check dams in a gully as physical soil conservation structures." Suggested OER search string: "bench terraces grass waterways check dams physical soil conservation OER diagram".
- Figure 5.8: Alley cropping system diagram Attribution: AI generated using prompt "Generate a diagram showing alley cropping with nitrogen-fixing shrubs on contours and food crops in the alleys, with pruning and mulch application shown." Suggested OER search string: "alley cropping nitrogen-fixing shrubs contours food crops mulch OER diagram".
- Figure 5.9: Sustainable soil management principles diagram Attribution: AI generated using prompt "Generate a pentagon or five-pillar diagram showing the five principles of sustainable soil management: minimum disturbance, permanent cover, plant diversity, organic matter replenishment, and living roots." Suggested OER search string: "sustainable soil management five principles minimum disturbance cover diversity OER".
- Table 5.1: Soil health indicators table Attribution: AI generated using prompt "Generate a table listing physical, chemical, and biological soil health indicators with target ranges for tropical agricultural soils and measurement methods." Suggested OER search string: "soil health indicators physical chemical biological target ranges OER table".
- Figure 5.10: Soil management and climate change diagram Attribution: AI generated using prompt "Generate a diagram showing how soil management practices provide adaptation benefits (water retention, erosion control) and mitigation benefits (carbon sequestration, reduced N2O) in response to climate change." Suggested OER search string: "soil management climate change adaptation mitigation carbon sequestration OER".