Soils and Agroforestry: General Principles

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Contents

Abstract

Proper management of soils has been central to the welfare of human society since very early times. An understanding of the nature and properties of soils is, indeed, critical to the success of any land-use system. Since the beginning of agricultural research in the mid-1800s, soils and soil-related aspects including plant nutrition were dominant themes in land-use R & D (research and development) portfolios all over the world. Thanks to these efforts, soil science has developed into a well-researched and prominent discipline endowed with a rich and voluminous literature base. This chapter presents a general introduction and briefly reviews the common terms used in soil science that are essential for understanding the major soil processes and ecosystem services. The topics and terms explained include those related to soil formation; physical, chemical, and biological properties of soils; soil types and classification; soil-derived

P. K. R. Nair et al., *An Introduction to Agroforestry*, https://doi.org/10.1007/978-3-030-75358-0_15

plant nutrients; soil management, and a brief note on some special characteristics of tropical soils. The major terms used in the chapter are also included in the Glossary of the book.

15.1 Introduction

Soil is one of the most important natural resources that supports all forms of terrestrial land use, and its proper management has been central to the welfare of human society since very early times. Food shortages caused by soil mismanagement and environmental destruction have undermined several ancient civilizations. The collapse of the Sumerian civilization in the Near East and the Mayan Empire of Mexico are two such classical examples narrated by Nair and Toth (2016). During the Sumerian civilization (that occupied a region in the lower valley of the Euphrates River, fifth to third millennium BC), a flaw in the irrigation practices led to rising water tables causing high soil salinity levels and serious crop failures. Once that tipping point was reached, starvation quickly destabilized and ultimately led to the demise of Sumerian society (Ponting 2007). As the Mayan Empire (Mexico, 2000 BC to 600 AD) continued to seek arable land and fuelwood, it encouraged deforestation leading to severe declines in soil productivity and high levels of soil erosion especially in the mountainous terrain of what is now Guatemala. The loss of productive capacity of the soils soon led to human malnutrition, leaving the weak society to warfare over limited resources and eventually the collapse of the Empire (Turner and Sabloff 2012). Based on such historical examples, as well as numerous experiences in the modern era, it became well recognized that an understanding of the nature and properties of soils is the key to the successful management of all land-use systems. Franklin D. Roosevelt, the 32nd President (1933–1945) of the United States who directed the federal government during most of the Great Depression (1929–1939), famously said: “A nation that destroys its soil, destroys itself.”

An understanding of the nature and properties of soils is, indeed, critical for understanding the principles of agroforestry and the success of the practice. The objective of this section of the book is to explain these principles of soil management for agroforestry and the potential benefits that could be derived by adopting science-based practices that are based on such principles. This chapter will present a general introduction including brief explanations of common terms used in soil science and elements of soil classification. The subsequent chapters will deal with major soil processes such as soil fertility improvement, organic matter dynamics, and nutrient cycling (Chapter 16), nitrogen fixation (Chapter 17), and soil conservation (Chapter 18). Ecosystem services, such as climate change mitigation through soil carbon sequestration, that are also intimately related to soil properties and management will be considered in the next section (Part V).

15.2 Soils and Agroforestry

One of the most widely acclaimed advantages of agroforestry is its perceived potential for conserving the soil and maintaining its fertility and productivity. Presumably, it was based on this premise that agroforestry came to be identified initially as a land-use activity in and for the tropics where the soils, in general, are inherently poorer and less productive than those in the temperate zones (this perception about the tropical focus of agroforestry, however, has changed since then: see Chapter 10). Consequently, and possibly because of the soil-science background and interest of several of the early researchers in agroforestry, soil productivity became one of the first areas of thrust in scientific agroforestry. The first international consultative scientific meeting organized by ICRAF was on soil research (Mongi and Huxley 1979), and a few other comprehensive reviews on this topic by ICRAF scientists were published during the 1980s (Nair 1984; Young 1989). This early momentum on soil-related investigations and initiatives has continued ever since in agroforestry R & D (research and development).

The prominence of soil-related issues in the AF research agenda is also a reflection of the overall prominence of soil research in the total research portfolio in all terrestrial land-use systems combined (agriculture, forestry, horticulture, grazing systems, etc.). Ever since the beginning of agricultural research (generally identified with the establishment of the Rothamsted Experiment Station, England, in the mid-1800s), soils and soil-related aspects including plant nutrition, have had a leading position in land-use R & D portfolio all over the world. Thanks to these efforts, soil science has developed into a well-researched and prominent discipline in the broad academic and scientific field and is endowed with a rich and voluminous literature base. Several comprehensive textbooks of soil science have been produced over the years; the currently popular ones with broad international appeal include N Brady and R Weil's *The Nature and Properties of Soils* (15th edition, Weil and Brady 2017; previous editions, e.g., Brady and Weil 2007), PA Sanchez's *Tropical Soil Management* (2nd edition, Sanchez 2019), and *The Encyclopedia of Soil Science* edited by R Lal, 3rd edition (Lal 2017). Another notable book is *The Ecology and Management of Forest Soils* (Fisher and Binkley 2000, and its multiple earlier editions) that is popular in forestry. Numerous other such publications focused on the soils of specific countries and regions are also available.

The fundamental aspects of soil science and principles of soil management are thus well established and are an essential part of the academic curricula of higher education in agriculture, forestry, and related disciplines around the world. It is neither necessary nor feasible to describe these in this context. Nevertheless, recognizing that several of those involved in agroforestry R & D may not be current on such fundamentals and also that it is important to have familiarity with these principles for understanding the issues, the common terms used in describing the nature, properties, and management of soils are explained here briefly. Although such explanations can be found in several textbooks and other resources, the authors of this book are convinced based on long years of their experience that asking a student or course participant to refer to some external sources other than the one being used as the main instructional resource is not as effective as having all the essential things grouped as one "bundle." Some such essential aspects including major properties and types of soils are described briefly in the following sections of this chapter. A summary of the terms and expressions that are commonly used in soil science and related fields is included. A good reference source for these terms is the *Soils Glossary* produced by the Soil Science Society of America (2020) (https://www.soils.org/publications/soils-glossary). Readers are encouraged to consult these, and other comprehensive literature sources referred to above for detailed information.

15.3 Soil Formation

15.3.1 How is the Soil Formed?

The soil that occurs on the land surface is a natural body consisting of solids (minerals and organic matter), liquids, and gases that can support rooted plants in a natural environment.

Soils are formed through a continuous process called weathering over millions of years, by which the original rocks and minerals on Earth's surface are transformed by physical disintegration and (bio)chemical decomposition. As represented by Hans Jenny's classical concept (Jenny 1941, 1980), $\mathbf{S} = \boldsymbol{f}\ \mathbf{(cl, p, o, r, t)}$, which signifies that soil formation through weathering (S) is influenced by five major factors: climate (cl), parent materials (p), biota or living organisms (o), relief, slope, and landscape position (r), and time (t, duration or length of soil formation).

***Climate* (cl)**: Precipitation and temperature are important factors in soil formation. Soil forms most readily under warm conditions such as in the tropical and temperate regions. This physical weathering process is also impacted by rainfall, ice, and wind, and by the roots of higher plants, sometimes called biological weathering (Figure 15.1), and by the impact of animals. Chemical weathering processes also proceed fastest under warm conditions.

Figure 15.1 Biological weathering of soils: physical weathering of soil hastened by biological factors, such as the presence of tree roots in dried and cracked soils in arid regions. (Source: Chittaakorn59 – Shutterstock)

Parent material **(p)**: Parent material includes different types of bedrock and glacial or stream deposits. When formed in place (i.e., if developed on the bedrock), soils are described as residual soils. Soils that develop on transported material (by gravity, water, ice, or wind) are sometimes referred to as "transported soil", although the soil itself is not transported.

Biota or living organisms **(o)**: Organic material accumulates in wet locations where the plant growth exceeds the rate of residue decomposition.

Relief, slope, and landscape position **(r)**: Soils develop best when the rate of soil formation is less than the rate of erosion. Therefore, steep slopes tend to have little or no soil. Also, topography influences the deposition of plant residues that form the parent material for organic soils.

Time **(t)**: Soils, in general, take thousands of years to develop. The process is so slow that it is difficult to measure changes in soil formation over time. Residual parent materials generally have been subjected to weathering conditions for longer periods compared to "transported soil."

15.3.2 Soil Horizon and Soil Profile

A *soil horizon* is a layer of soil approximately parallel to the land surface, differing in properties (physical, chemical, and biological) and characterizations from the layers above and below it.

A *soil profile* is a vertical section of soil from the surface through all its horizons and extending into the C horizon (Figure 15.2).

15.4 Soil Properties

15.4.1 Physical Properties

Soil Structure describes the arrangement of the solid parts of the soil (sand, silt, clay) and the pore space located between them. Single particles when combined appear as larger particles or aggregates. They are held together by moist clay, organic matter, gums (from bacteria and fungi), and fungal hyphae.

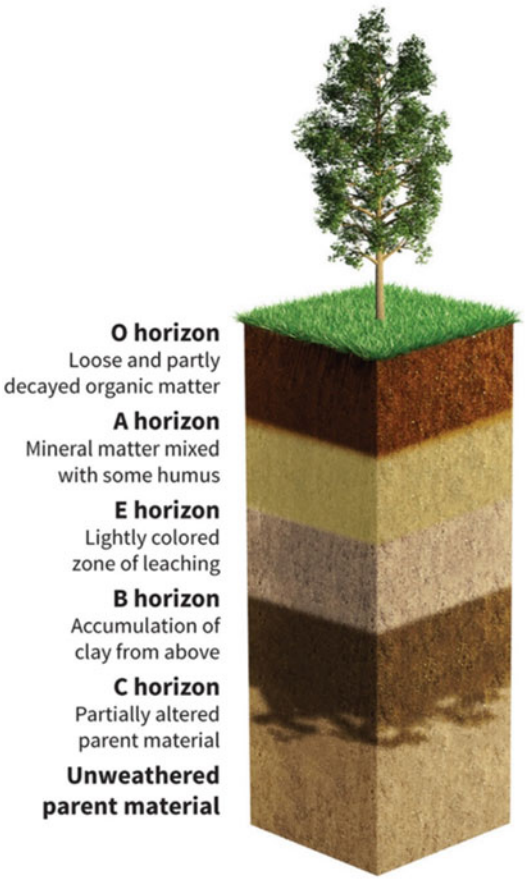

Figure 15.2 Vertical section of a soil profile from the surface to the parent material

Soil Aggregates range from 0.002 mm to 2.00 mm. They can resemble various shapes such as granular, blocky, and crumb. These varied shapes allow for healthy soil to have pore spaces for air and water needed for healthy plant growth. Aggregates are formed through physical, chemical, and biological activities. Well-aggregated soils generally have greater soil health, ensure better agricultural productivity, and play a vital role in soil carbon sequestration.

Soil Texture refers to the proportions of sand, silt, and clay particles in the soil (Figure 15.3). The sand, loamy sand, and sandy loam groups are further subdivided depending on the proportions of sand present. The USDA (US Department of Agriculture) "soil texture triangle" (Figure 15.4) is used for determining the textural class of the soil based on the relative proportions of sand, silt, and clay. For example, a soil with 42% sand, 35% silt, and 23% clay is a "loam." A soil with 8% sand, 60% silt, and 32% clay is a "silty clay loam." Soil texture is also expressed qualitatively as "texture by feel." ***Soil texture*** and ***soil structure*** are both unique properties of the soil that will have a profound effect on its behavior, such as water holding capacity, nutrient retention and supply, drainage, and nutrient leaching.

Soil Color is derived from the minerals present in the soil as well as the organic matter content. For example, yellow or red soil indicates the presence of ferric iron oxides. Organic matter makes the soil color darker.

Soil Bulk Density is dependent on the mineral makeup of the soil and the degree of compaction. It is calculated as the dry weight of the soil divided by its volume (total volume of soil particles and the volume of pores between them, and hence the term "bulk density"). The high bulk density of soil is an indicator of low soil porosity and soil compaction.

How heavy is a soil?

A typical medium-textured mineral soil with a bulk density of 1.15 Mg m^{-3} weighs 1,250 kg m^{-3} (2,015 pounds per cubic yard)

A hectare furrow slice of a typical soil weighs ~ 2.2 million kg (~ 2 million pounds per acre)

15.4.2 Chemical Properties

Soil Reaction: Acidity, Salinity, and Alkalinity. The term soil reaction, although no longer used in soil science (Weil and Brady 2017), refers to its degree of acidity or alkalinity usually expressed as a pH value (range: 0–14), which is the measure of the hydrogen ion concentration of a solution with a pH of 7 indicating neutrality (neither acidic nor basic) (Figure 15.5). The pH of a soil solution is measured at a specified soil to solution ratio in a specified solution, usually distilled water, 0.01*M*

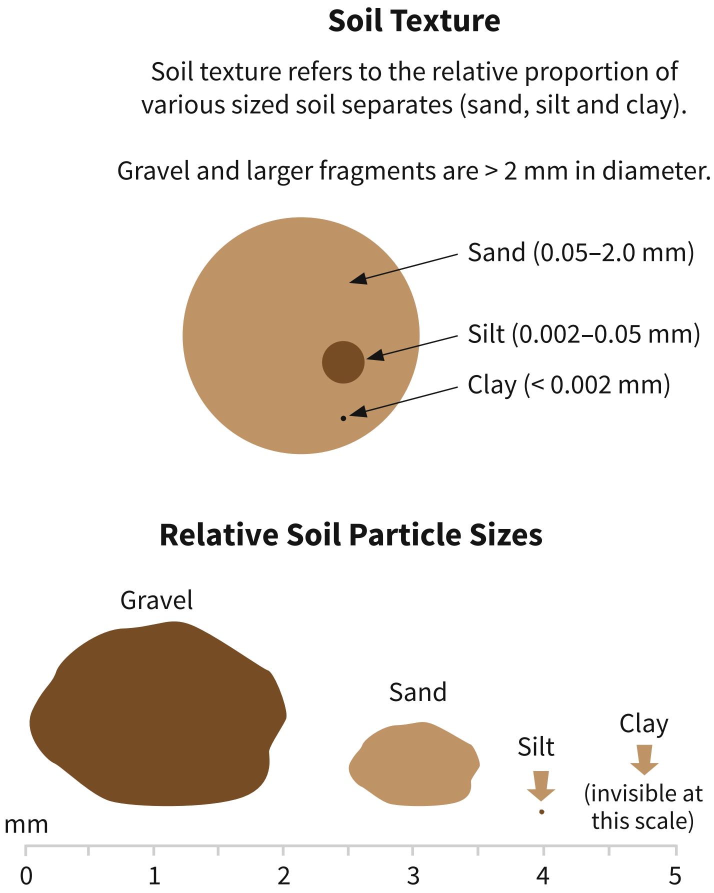

Figure 15.3 Relative proportion of soil particle sizes (sand, silt and clay). Reproduced from https://i.pinimg.com/originals/32/2b/04/322b0462355c74141cade1bfe72e6e2a.jpg

calcium chloride, or 1*M* potassium chloride. While the optimal soil pH range for most plants is between 5.5 and 7.0, many plants thrive at levels outside this pH range. Soil pH is important because it influences the availability of essential nutrients. Soil salinity refers to the amount of soluble salts in the soil; the process of increasing the salt content is known as salinization. Saline and alkaline soils contain relatively high contents of salts. Saline soil is nonsodic and does not contain sodium at levels that interfere with the growth of common crops but contains other soluble salts at levels sufficient to impair crop production, with the exchangeable sodium adsorption ratio < 15 and pH > 8.5. Alkaline soil has high levels of sodium to interfere with the growth of most crops, with an exchangeable sodium adsorption ratio > 15 and pH > 9.00.

Cation (and Anion) Exchange. Cation exchange is the exchange of ions between two electrolytes or between an electrolyte solution and a cation in the boundary layer between the solution and a negatively charged material such as clay or organic matter; anion exchange refers to the exchange of negatively charged ions. The ability of the negatively charged material to retain and release positively charged ions controls the mobility of the chemical species – such as potassium from fertilizers – in the soil solution.

The soil's **Cation Exchange Capacity** (CEC) is a soil's total capacity for holding exchangeable cations, which are positively charged ions – calcium (Ca^{2+}), magnesium (Mg^{2+}), sodium (Na^+), and potassium (K^+). Anion exchange capacity (AEC) is the ability of a soil to adsorb or release anions from a soil. The soil exchange capacity is

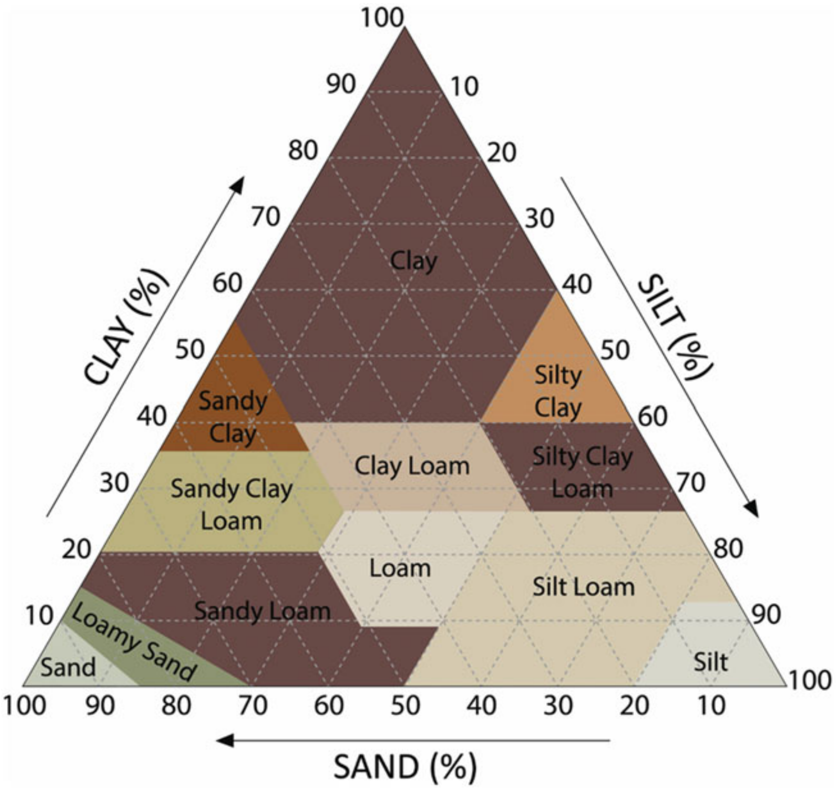

Figure 15.4 USDA Textural Classes as defined by the "textural triangle"

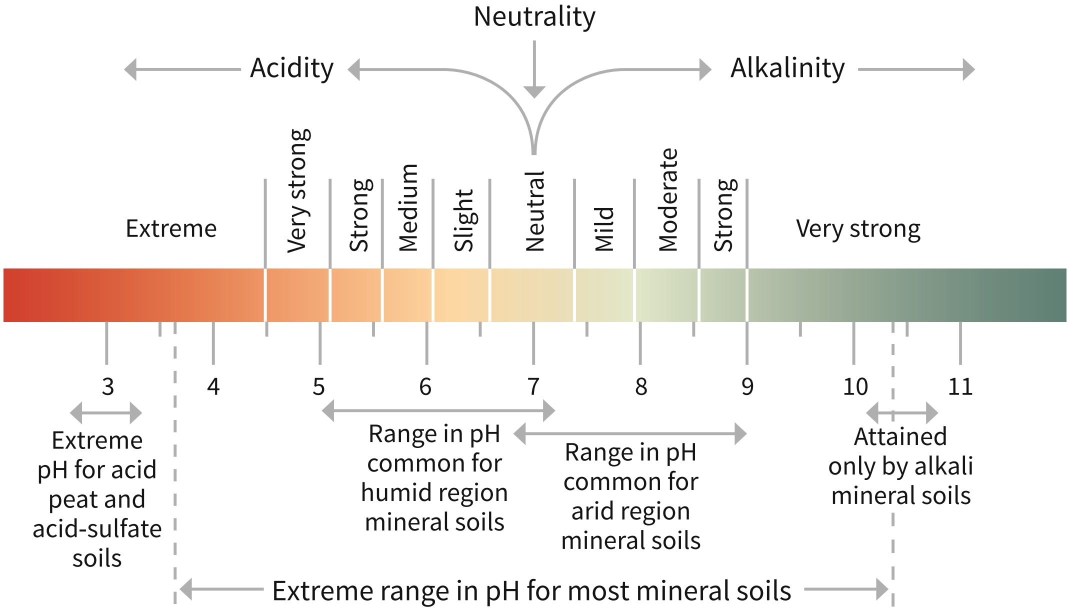

Figure 15.5 Range in pH for mineral soils including ranges commonly found in humid region and arid region soils. pH ranges: Very strongly acid, <4.5 – 5.0; Strongly acid, 5.1 – 5.5; Medium acid: 5.6 – 6.0; Slightly acid, 6.1 – 6.5; Neutral, 6.6 – 7.3; Alkaline, >7.3

therefore the total capacity of soil to hold exchangeable ions and thereby influences the soil's ability to retain nutrients.

Soil Colloids and Layer Silicates. The clay and humus particles that are extremely small and have colloid-like behavior are collectively called the **colloidal fraction**. These particles are about 1 μm in diameter and therefore have a large external surface area per unit mass, more than 1000 times the surface area of the same mass of sand particles. The silicate clays have an extensive internal surface area between their plate-like crystal units. The cations that are held on (adsorbed) by electrostatic attraction to negatively charged soil colloids are replaced by other cations through cation exchange**.**

Soils contain several types of colloids, such as crystalline silicate clays (e.g., kaolinite and smectite), non-crystalline silicate clays (e.g., allophane), iron- and aluminum oxides (e.g., gibbsite and goethite), and organic (humus) colloids. The crystalline silicate clays that are dominant in most soils are layered like the pages in a book and consist of sheets of closely packed and tightly bonded oxygen, silicon, and aluminum atoms. Depending on the number and arrangement of these "sheets," crystalline clays are classified into two main groups: 1:1 and 2:1 silicate clay. The 1:1 clay has one silicon and one aluminum sheet, and the 2:1 has two silicon sheets with one aluminum sheet in between. Kaolinite is the major type of 1:1 clay, and smectite (of which montmorillonite is the most prominent form) the major type of 2:1 clay in soils. The type of silicate clays in a soil has major influences on its physical and chemical properties.

Heavy Metals and Toxicity. Soils could become contaminated by the accumulation of heavy metals (lead, copper, arsenic, mercury, and zinc) released into the environment during disposal of industrial wastes, land application of fertilizers, and sewage sludge to name just a few sources. Such material could provide risks and hazards to humans (via contaminated food and water) and the environment. Agroforestry practices have a remarkable potential to remediate such soils (Chapter 22).

15.4.3 Biological Properties

The biological properties of soils arise from the soil biota that comprises large numbers of diverse organisms that live in them. These include microorganisms (such as bacteria, fungi, protozoa, viruses, and nematodes), mesofauna (collembola, mites, etc.), and macrofauna (earthworms, millipedes, termites, ants, beetles, and other invertebrates). It is estimated that 10–100 million organisms of more than 5000 taxa exist in just a handful of soil (Sanchez 2019). Together these organisms provide numerous essential ecosystem services that are critically important for humans and overall life on planet Earth. These include decomposition of organic matter, the transformation of plant nutrients, nitrogen fixation, soil structure regulation, and extension of plant root functions through mycorrhizal association. Soil microorganisms also include some plant and animal pathogens as well.

15.5 Soil Types and Soil Classification

Soils vary widely in their nature and properties. Farmers knew this for a long time, and they used to allocate different crops to soils depending on their judgment on crop – soil suitability, i.e., most suitable soil for a particular crop and the best crop/s suitable for a particular soil. Gradually, different descriptive terms emerged to designate soils according to their suitability for specific major crops (such as *black cotton soils* and *rice soils*) and on the parent materials of the soils (such as *limestone soils* and *alluvial soils*). The color and predominant textural composition of the soil have also been used for a long time to indicate the soil type; thus, terms such as *red soils, black soils,* and *sandy soils* are popular in common parlance even today. It is not unusual to hear the soil being referred to as "dirt," but such denigratory expressions can be dismissed outright as meaningless rants by the ignorant. While the various local terms used for limited purposes have their own value, they are inadequate for defining and comparing different soils and organizing the scientific knowledge that has been continuously becoming available.

As unbelievable it may sound, there is still no universally accepted soil classification scheme despite the tremendous advances that have been made in the field of soil science. This creates a strange situation that hinders "proper communication" (in terms of technical details) even among soil scientists from different parts of the world. Over the past several decades, several soil-classification schemes have been used around the world as described by Krasilnikov et al. (2009). The underlying concepts of these schemes are of two broad categories: soil genesis (soil formation with emphasis on how the soil has originated; Section 15.3.1) and soil morphology and properties (field observable attributes of the soil). Gradually, soils began to be classified and recognized as natural bodies, based not just on their color, location, or suitability for a specific crop or group of crops, but on their "individuality," i.e., profile characteristics. Thus, soils with similar properties at different locations can be classified similarly, and the research experience gained from one location can generally be used to predict the behavior of similarly classified soils from other locations. Based on these two major approaches to soil classification (soil genesis and morphology), two major systems of soil classification are currently used; the USDA Soil Classification (Soil Taxonomy) system (Soil Survey Staff 2014), and the United Nations-sponsored WRB system (World Reference Base) for Soil Resources (Bridges et al. 1998). Various national and regional classification schemes such as the European, French, Belgian, Brazilian, Indian, etc. that were in prevalence have now mostly been replaced by the UN-sponsored WRB system.

15.5.1 The USDA Soil Classification (Soil Taxonomy)

The USDA system of soil classification is a hierarchical system with six categories: order, suborder, great group, subgroup, family, and series. Twelve soil orders have been identified (Figure 15.6); their names and formative terms are given in Table 15.1, and the general degree of weathering and soil development for different orders are presented in Figure 15.7.

The orders and taxonomic properties often relate to Greek, Latin, or other root words with some relationship that explains the properties of the soil. The nomenclature of the different categories in the USDA-NRCS (Natural Resources Conservation Service) classification system is illustrated below using Mollisols, the highest percentage of ice-free land areas in the United States, and Entisols the highest percentage globally (Table 15.2) as examples.

Soil order: M*oll*isols
Suborder: Aqu*oll*s
Great group: Argioqu*oll*s
Subgroup: Typic Argioqu*oll*s

The "*oll*" identifies the lower categories as being a part of the M*oll*isols soil order.

The family name identifies subsets of the subgroup that are similar in texture, mineral composition, and mean soil temperature at a depth of 50 cm. Thus, the name **Typic Argiaquolls, fine mixed, mesic** identifies a family in the Typic Argioquolls subgroup with a fine texture, mixed clay mineral content, and mesic (18 to 15 °C) soil temperature (Weil and Brady 2017)

Soil order: Entisols. Several suborders exist in different parts of the world, e.g., i) Psamments (sandy; typical of the Saharan desert and Saudi Arabia, dominant parts of southern Africa and central and north-central Australia and also parts of the US), ii) Fluevnts (alluvial deposits; predominant in the intensively cultivated rice lands of Asia), iii) Orthents (typical; northern Quebec and parts of Alaska, Siberia, and Tibet), iv) Aquents (wet; flooded area around the Mississippi River). Entisol characteristics are highly variable and any generalization of agricultural management in these soils is difficult (Weil and Brady 2017).

15.5.2 The US Soil Taxonomy and UN (FAO/UNESCO) Soil Classification

The hierarchical organization of the US Soil Taxonomy is helpful – despite some initial difficulty

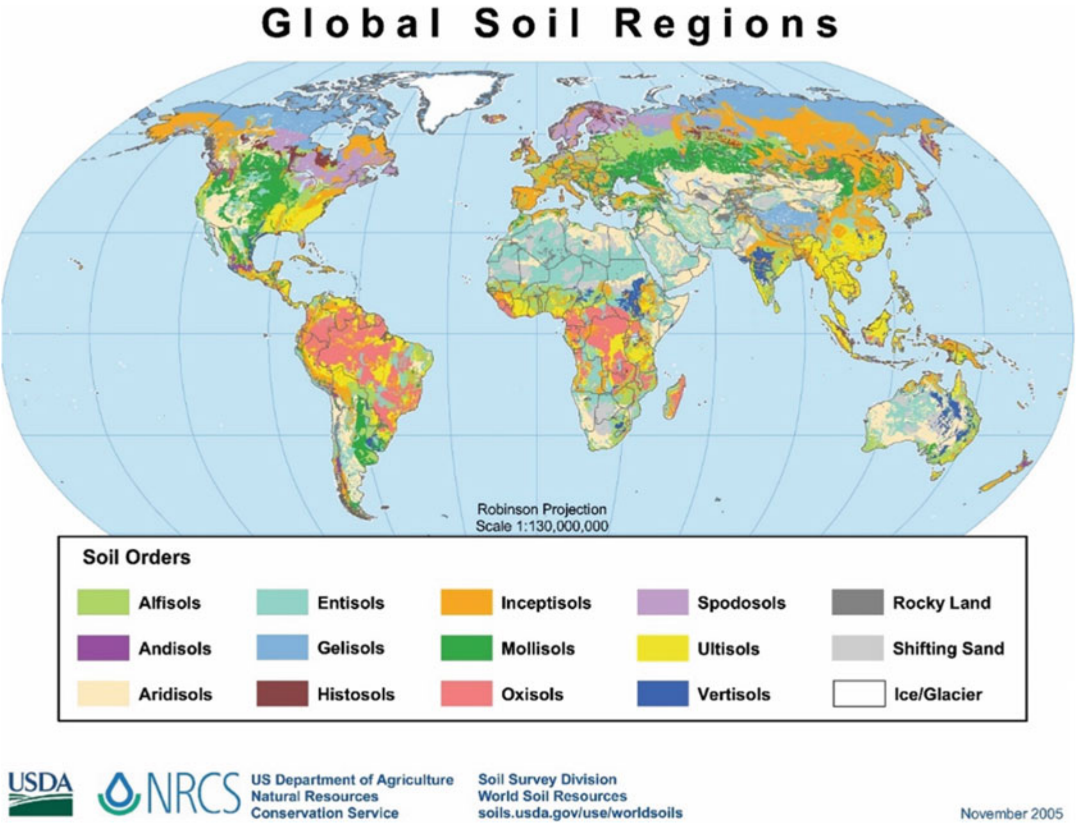

Figure 15.6 Global soil orders (USDA-NRCS 2005)

Table 15.1 Soil orders and their formative terms

Soil Order	Formative Terms
Alfisols	Alf, refers to Al and Fe
Andisols	Japanese, ando, dark
Aridisols	Latin, aridies, dry
Entisols	Ent, no specific meaning
Gelisols	Latin, gelare, to freeze
Histosols	Greek, histos, tissue
Inceptisols	Latin, inceptum, beginning
Mollisols	Latin, mollis, soft
Oxisols	French, oxide
Spodosols	Greek, spodos, wood ash
Ultisols	Latin, ultimus, last
Vertisols	Latin, verto, turn

in getting familiar with the terms – for examining relationships between different types of soils, where they are found, and what their properties and uses are. A USDA-NRCS soils map (USDA-NRCS 2005) is presented in Figure 15.6. This system of soil classification, although still not universally used, will be used in this book.

The other commonly used soil classification scheme is the WRB (World Reference Base; still sometimes called “the FAO Soil Classification”).

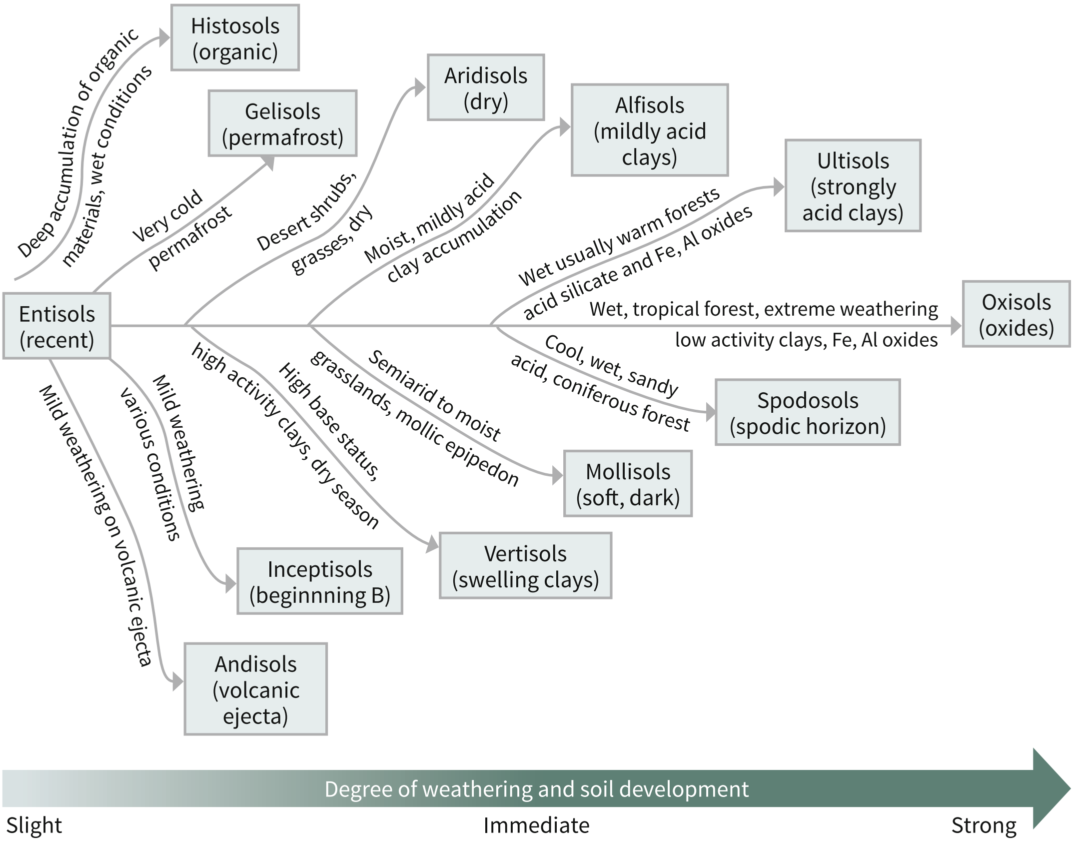

Figure 15.7 Diagram showing the general degree of weathering and soil development in the different soil orders classified in Soil Taxonomy. Also shown are the general climatic and vegetative conditions under which soils in each order are formed. Reproduced with permission from Brady and Weil (2008)

The United Nations Food and Agriculture Organization (FAO), in association with the U.N. Educational, Scientific, and Cultural Organization (UNESCO) prepared successive versions of a comprehensive *World Soil Map* during the 1970s. A revised legend was published in 1988. The World Soil Map was digitized and made available in 1995 (FAO/UNESCO 1995). The FAO legend was transformed into the WRB as a soil classification system with more quantifications, closely corresponding to the soil order categories, but not identifying all the suborders, of the Soil Taxonomy (Bridges et al. 1998, Deckers et al. 1998). Because of the international character of the FAO legend (WRB), it is widely used in many countries. Table 15.3 gives the approximate terms used for the major soil orders in the two soil classification schemes. Although the terms are somewhat equivalent, they are not readily interchangeable.

15.6 Plant Nutrients in Soils

Essential plant nutrients are those elements that are essential for the growth of all plants; i.e., without them, the plants would not grow. Of these, carbon (C), hydrogen (H), and oxygen (O) are taken up from air and water, and the rest from soils. Some other elements are taken up by some plants, but they are not essential for all, and therefore do not meet the criteria of essentiality. These include silicon (Si), selenium (Se), chromium (Cr), cobalt (Co), vanadium (V), and sodium (Na); some elements, which, if taken up in excess quantities could be toxic to plants (see Section 15.4.2, Heavy and Toxicity). Three elements [Nitrogen (N), phosphorus (P), and potassium (K)] that are needed by plants in relatively large quantities are called macronutrients. Calcium (Ca), magnesium (Mg), and Sulfur (S) are sometimes called secondary nutrients; these are needed by plants in relatively large quantities, but more than fulfilling their physiological functions in plants, they are also applied to soils in relatively large quantities as soil amendments to correct adverse soil conditions such as acidity and alkalinity. The other eight essential elements that are needed by plants in relatively very small quantities are called micronutrients. The various essential elements, their average concentrations in plants, and the ionic (or molecular) forms in which they are taken up by plants are shown in Table 15.4. A jingle that is commonly used to remember these 17 essential elements reads as follows: CHOPKiNS CaFe M(a)naged By Close C(o) uZ(i)n MoNi, that should sound like an easy-to-remember line "C Hopkins Café Managed by Close Cousin Moni."

15.7 Tropical Soils

Soil productivity is particularly relevant in the tropics where the soils are, in general, inherently poor and less productive (than in the temperate zones). Geographical distribution of soil orders in the tropical continents (Africa, the Americas, and Asia), based on the dominant soil in FAO maps is given in Table 15.2.

The highly weathered and leached acid infertile soils (Oxisols and Ultisols) that dominate the humid tropics constitute more than 40% of the tropical soils. Soils of moderate to high fertility (Alfisols, Vertisols, Mollisols, Andisols) constitute about 23%. Dry sands and shallow soils (Psamments, Entisols) and light-colored, base-rich acidic groups (Aridisols) account for about 17% of the tropical soils, and the remainder consists of various other soil groups.

The main soil-related constraints to plant production in these major soil groups of the tropics are summarized in Table 15.3. In general terms, Oxisols, Ultisols, and other highly weathered and leached soils have low exchangeable base contents, low nutrient reserves, high aluminum

Table 15.2 Approximate global land areas of different soil orders as percentages of the ice-free land, with their major land-uses and natural fertility status

Soil Order USDA Taxonomy	Global area		Tropical area		Major land uses	Natural fertility
	million hectares	%	million hectares	%		
Alfisols	1263	9.7	480	12.4	Crops, forest, range	High
Andisols	90	0.7	45	1.2	Tundra, forests, crops	Moderate to high
Aridisols	1578	12	186	4.8	Range, crops	Low to moderate
Entisols	2113	**16.2**	603	15.6	Range, forests, crops, wetlands	Low to moderate
Gelisols	1126	8.6	0	0	Tundra, bogs	Moderate
Histosols	153	1.2	32	0.8	Wetland, crops	Moderate to high
Inceptisols	1275	9.8	606	15.7	Forest, range, crops	Low to high
Mollisols	899	6.9	36	0.9	Forest, range, wetlands	High
Oxisols	981	7.5	962	24.8	Forests, crops	Low
Spodosols	336	2.6	6	0.2	Forest, crops	Low
Ultisols	1102	8.5	760	19.6	Forest, crops	Low to moderate
Vertisols	319	2.4	150	3.9	Crops, range, wetlands	High

Adapted from Sanchez (2019)

Table 15.3 Soil characteristics and classification according to US Soil Taxonomy and FAO Systems

US Soil Taxonomy	FAO	Description
Alfisols	Luvisols, Eutric, Nitosols, Planosols and Lixisols	Higher base status than Ultisols, but similar otherwise. Includes the more fertile tropical red soils. Dominant of west African subhumid tropics and savannas
Andisols	Andosols	Volcanic soils, moderate to high fertility, P fixation by allophane
Aridisols	Solonchak and Solonetz	Main limitation is moisture availability
Entisols	Various:	Young soils without A-B-C horizon development; generally high fertility except for sandy soils
Fluvents	Fluvisols	Alluvial soils usually of high fertility
Psamments	Arenosols and Regosols	Sandy, acid, infertile soils
Gelisols	Cryosols	Perennial frozen soils of the Artic and Antartica regions; also found at extremely high elevations in lower latitudes
Histosols	Histosols	Organic soils (> 20 % organic matter). Peat soils
Inceptisols	Various:	Young soils with A-B-C horizon development. Fertility highly variable
Aquepts	Gleysols	Poorly-drained moderate to high fertility
Tropepts	Cambisols	Well-drained Inceptisols (Dystropepts=acid, infertile; Eutropepts=high base status)
Mollisols	Chernozems	Black fertile soils derived from calcareous materials
Oxisols	Ferralsols	Deep, highly weathered, acid, low base status soils.
	Plinthisols	Excellent structure and good drainage. No significant increases in clay with depth
Spodosols	Podzols	Sandy surface horizon underlain with a horizon of organic and amorphous C, Fe and Al compounds. Acid and infertile
Ultisols	Acrisols, Dystric, Nitosols and Alisols	Similar to Oxisols except for a clay increase with depth.
		Similar chemical limitations. Textures from sandy to clayey
Vertisols	Vertisols	Dark heavy clay soils that shrink and crack when dry.
		Moderately high base status

Modified from Szott et al. (1991) and Nair (1993)

Note: Histosols are organic soils (as opposed to mineral soils) with ~1.2% occurrence globally

toxicity, low phosphorus availability, and high to medium acidity. These soils are called the Low Activity Clay (LAC) soils, indicating that their exchange complex is dominated by clay minerals with low cation exchange capacity (CEC), such as the 1:1 layer silicates of the kaolin group, and are therefore usually infertile. Ultisols can have larger problems with aluminum toxicity, whereas Oxisols are apt to be low in potassium, calcium, and magnesium; these soils also have high phosphorus fixation and hence low phosphorus availability. Spodosols and Psamments (sandy soils) are especially low in nitrogen, phosphorus, and bases. Although moisture availability is the most limiting factor to plant production in the dry (subhumid, semiarid, and arid) areas, low nutrient reserves could also be an equally serious problem (Szott et al. 1991).

Myths and misconceptions also abound about tropical soils, their nature, and productivity. For example, in many scientific and technical publications, tropical soils are described as or considered to be, universally infertile, and often incapable of sustained agricultural production. But such conjectures are not supported by scientific evidence. The Soil Science Society of America published a book (Sanchez and Logan 1992) in which leading soil scientists of the world discuss these widely-held misconceptions about tropical soils, and argue that several of the myths and misconceptions are based on inadequate information on principal soils of the region, the interaction between soils and prevalent climate, soil physical and mineralogical properties, soil chemical and nutritional characteristics, and soil microorganisms and their effect on soil

Table 15.4 The essential elements (plant nutrients), their average concentrations in plants and the form in which they are taken up by plants

Category of Essential Elements	Nutrient	Average concentration in plant biomass	Taken up as (ion or molecule)
Essential Elements	Carbon	45 %	CO_2
	Oxygen	40%	CO_2, H_2O, other ions
	Hydrogen	5%	H_2O
Macronutrients	Nitrogen	2.5%	NO_3^-, $NH_{4-}{}^+$
	Phosphorus	0.2%	H_2PO^{4-}, HPO_4^{2-}
	Potassium	1.75%	K^+
Secondary Nutrients	Calcium	1%	Ca^{2+}
	Magnesium	0.5%	Mg^{2-}
	Sulfur	0.3%	SO_4^{2-}
Micronutrients	Chlorine	100 ppm[a]	Cl^-
	Iron	100 ppm	Fe^{2+}, Fe^{3+}
	Manganese	50 ppm	MnO_4^{2-}
	Boron	30 ppm	BO_3^{3-}, H_3BO_3
	Zinc	20 ppm	Zn^{2+}
	Copper	5 ppm	Cu^{2+}
	Nickel	1 ppm	Ni^{2+}
	Molybdenum	0.1 ppm	MoO_4^{2-}

Adapted from Sanchez (2019)

[a] ppm = parts per million; corresponding SI unit = milligrams per liter

productivity. The main conclusions of this significant publication are:

- soils of the tropics are very diverse, their diversity being at least as large as that of the temperate zone;
- while it is true that rates of organic matter decomposition are higher and therefore it is more difficult to maintain organic matter levels in the tropical as compared to temperate soils, there is no difference in quality and effectiveness of humus in tropical and temperate soils;
- indeed, the soils of the tropics are generally poor in their fertility compared with temperate soils; however, the chemical processes involved in the maintenance of the soil's fertility and chemistry are the same regardless of latitude; what is different is their management, because of the different climate, crop species, and socioeconomic conditions found in the tropics;
- a vast majority of tropical soils are characterized by a weak structure prone to slaking, crusting, compaction, and a rapid loss of infiltration capacity; such weakly formed structural units slake readily under the impact of high-intensity rains, so that accelerated erosion is a severe hazard on most tropical soils with undulating to sloping terrain;
- factors such as rainfall pattern, rainfall intensities, potential evapotranspiration, waterlogging, temperature, and wind should be carefully considered while assessing soil productivity in the tropics;
- a delicate balance exists within the soil/plant continuum in the tropics; management practices that must include efficient use of fertilizers must be developed to sustain the productivity of this continuum; and
- many soils in the tropics do not contain indigenous rhizobial populations in adequate numbers to meet symbiotic N_2- fixation by leguminous crops.

15.8 Soil Health

The USDA-NRCS defines soil health as "**the continued capacity of soil to function as a vital living ecosystem that sustains plants,**

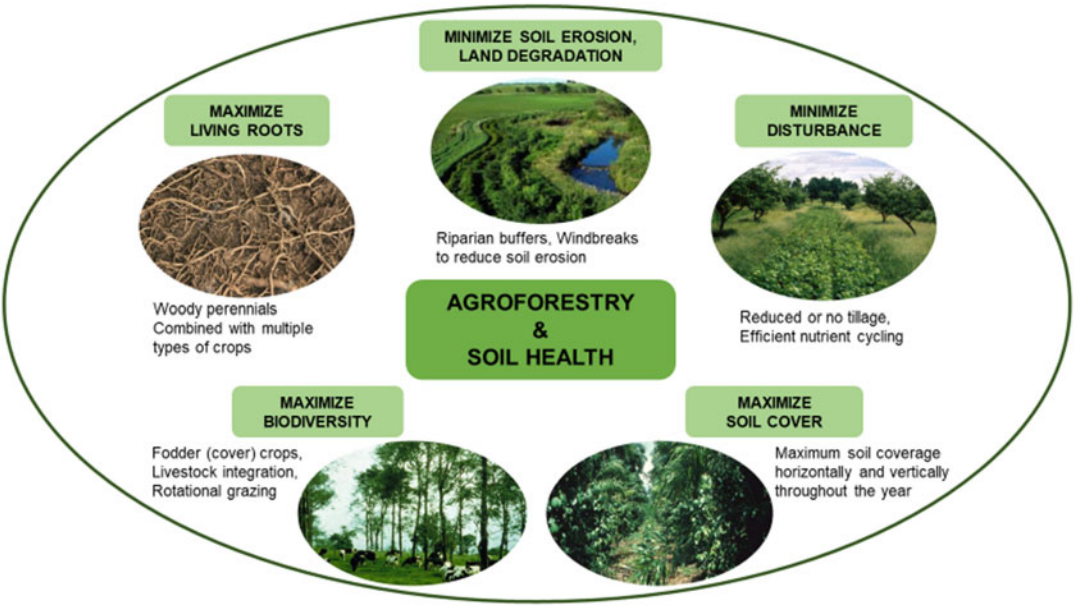

Figure 15.8 Agroforestry and Soil Health. The figure illustrates how the five key principles of soil health identified by USDA-NRCS are fulfilled by different representative examples of agroforestry practices. Source: Adapted from NRCS https://www.climatehubs.usda.gov/hubs/northwest/topic/soil-health-management-reduce-climate-and-weather-risks-northwest

animals, and humans" (https://www.nrcs.usda.gov/wps/portal/nrcs/main/soils/health**)**. This definition highlights the importance of managing soils as a living resource so that they are sustainable for future generations.

Soil health is not a new concept; for example, Doran et al. (1996) have articulated the importance of soil health in sustainability. Wikipedia explains soil health "as a state of a soil meeting its range of ecosystem functions as appropriate to its environment," and that "in more colloquial terms, the health of soil arises from favorable interactions of all soil components (living and non-living) that belong together, as in microbiota, plants, and animals." Therefore, soil health cannot be defined in abstract quantitative terms. Because of that reason, soil health is explained in different ways, most of which arise from the perception that "Soil health is an indicator of how well the soil does what we want it to do."

Soil health has attained considerable significance lately in the context of the environment and climate-change discussions that have dominated the international arenas for the past two decades, wherein soils have been recognized as a potential sink for carbon and greenhouse gases. In this context, the role of tree-based land-management practices such as agroforestry is particularly relevant. Based on the USDA-NRCS portrayal of how different land-management practices fulfill the key principles of soil health, Figure 15.8 depicts how these principles are fulfilled by different agroforestry practices. Detailed discussions and illustrations of how each of these is fulfilled are presented in the subsequent chapters of the book.

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