Chapter 6

Soil Physical Quality Indicators and Plant Growth

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Abstract

Soil physical quality parameters are playing key role in understanding the soil performance regarding plant growth and development. Some of these health indicators directly carry their impact on crops and plants, while others effect indirectly by affecting other chemical and biological soil quality parameters. Now a day's soil health and quality are gaining more impotence worldwide. Actually these two words are considered differently but are synonymous. The inherent soil quality addresses soil aspects which are related to the soils natural composition and properties affected by soil formation factors and processes. In this chapter we have covered the soil quality parameters which will furnish the reader about the soil texture, structure and many others properties which in turn will determine soil water holding capacity, nutrients holding capacity and its cycling, soil infiltration and ultimately selection of crops for a particular area in a region, soil carbon sequestration and NO_3 leaching. Soil aeration and temperature are key factors deciding the functioning of microbial community which will be determined according to soil redox potential and biochemical oxygen demand. We have emphasized not only on soil physical quality parameters but also on chemical and biological soil quality indicators. The soil health is the integrated approach to integrate all the parameters to sustain our crop productivity which has become stagnant at one point for many years.

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6.1. Introduction

Soils are complex medium, made up of a heterogeneous mixture of solid, liquid, and gaseous phases, as well as a diverse community of living organisms. Soil quality is a measure of the ability of a specific kind of soil to function, within an ecosystem and land use boundaries, to sustain animal and plant productivity, maintain environmental quality and promote human health and habitation. The concept of soil quality deals with integrating and optimizing of physical, chemical and biological components of soil for improved productivity and environmental quality. The potential soil physical indicators used in soil quality assessment comprised of bulk density, pore-size distribution, available water capacity, aggregate stability, surface and sub-surface penetration resistance, saturated hydraulic conductivity and water infiltration. In addition to soil physical quality indicators, other physical properties of soil are also discussed as these are not included in other chapters of this book. The soil properties that we can see or feel are physical and include texture, structure, particle and bulk density, pore space, aeration, water, consistence, color and temperature.

6.2. Soil Texture

Soil texture refers to the relative proportion or percentage distribution of sand, silt and clay in a less than or equal to 2 mm soil called fine-earth fraction. It is relatively a static property and is difficult to change through soil use and management. Soil inorganic fractions that are greater than 2 mm in diameter are referred as coarse fragments. Soil particles larger than 2 mm but less than 250 mm, i.e. between gravels and cobbles, are considered as part of soil as they greatly influence its behavior or use. If they are more than 15 % by volume in whole of the soil, they are used as modifier of textural class names, e.g., gravelly loam and cobbly sandy loam.

6.2.1. Classification of soil separates

The mineral soil particle-size groups are referred as soil separates. Several systems of soil separate classification have evolved over a period of time. The two classification systems, the International Society of Soil Science (ISSS) system and the U.S. Department of Agriculture (USDA) system are used by soil scientists. Coarse sand (2000 – 200 μm), fine sand (200 – 20 μm), silt (20 – 2 μm) and clay (< 2 μm diameter) are the four particle-size fractions that define the soil separate classes according to ISSS system. The size ranges of soil separates followed by USDA system are: Very coarse sand (2000 – 1000 μm), coarse sand (1000 – 500 μm), medium sand (500 – 250 μm), fine sand (250 – 100 μm), very fine sand (100 – 50 μm), silt (50 – 2 μm) and clay (< 2 μm). The classes of coarse fragments are gravels

(2 – 75 mm), cobbles (75 – 250 mm), stones (250 – 600 mm) and boulders (> 600 mm diameter).

6.2.2. Nature of soil separates

The fine-earth fraction is the most active fraction of the soil as it has the greatest specific surface area. It controls important properties of most soils. The clay fraction has a significant effect on many soil physical and chemical properties, largely since the small-sized particles have large and reactive surface area. On the contrary, the sand and silt fractions usually do not have much influence on chemical processes, and their relatively small surface areas do not adsorb or hold water as much as clay fraction does. As a result, the sand and silt fraction of the soil matrix may be regarded as an inert entity whose impact on soil water is expressed primarily by the geometric arrangement of the soil particles. The coarse fragments can cause hindrance in cultivation, may damage tillage implements and influence land use greatly.

As clay fraction has a definitely different effect on soil water and solutes than sand or silt, one could make some generalizations about various characteristics of field soils that contain dominant quantities of one or the other of the three fractions. For instance, sandy soils do not hold considerable quantity of water, thus need more frequent irrigations to avoid plant water stress than do soils in the same type of weather that contain large quantity of clay.

Soils are given different textural class names based on the quantities of sand, silt, and clay particles present in them. The USDA textural triangle is an appropriate method of presenting the relationship between the soil textural class name and soil separates (Fig. 6.1; Gee and Or 2002).

Two procedures, mechanical sieving (if particle size > 50 μm) and sedimentation (if particle size < 50 μm), are used to measure the size of individual soil particles. A soil sample whose mineral phase is to be characterized is first pretreated to remove organic material and other cementing agents to disperse soil aggregates. Then the completely dispersed soil particles are passed through a series of coarse screens of specified opening sizes with the smallest screen having an opening of about 50 μm. The sizes of the remaining dispersed particles (silt and clay) are determined by sedimentation procedures using either the hydrometer method or the pipette method. Both methods are based on Stokes' law, which is used to establish a relationship between the settling velocity (V) of particles and the particle sizes.

In the hydrometer method, density of soil suspension is measured after various time intervals because density decreases with time due to settling of particles. The hydrometer method is simple, rapid and more widely used but is less accurate than pipette method (Gee and Or 2002). The pipette method consists of direct sampling of the soil suspension with a pipette at a certain depth (usually 0.1 m) after various time intervals depending on temperature of the suspension. The pipette method is accurate but is laborious and time consuming.

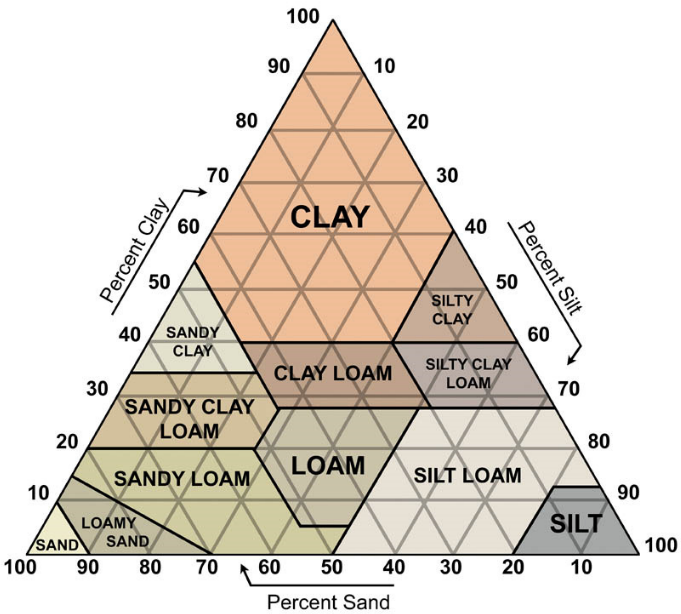

Fig. 6.1 USDA textural triangle for soil textural class determination

6.3. Soil Structure

Soil structure refers to the grouping or combination of primary soil particles into secondary particles called aggregates or peds, which are separated from each other by natural lines of weakness. Soil structure is better studied in undisturbed soil under field conditions than in the laboratory. Soil structure may be classified into three main structural groups: single-grained, massive, and aggregated. The single-grained refers to the geometric arrangement of soil particles into a porous formation, with little or no cementation or flocculation among its constituents. Coarse-textured sands frequently orient in this manner and often are called structure-less. A massive structure represents the opposite extreme of a complete consolidation of soil with no natural lines of weakness and generally occurs in fine textured soils. In between these two extremes are aggregated soils, in which soil separates stick together to form larger units or aggregates. Natural soil aggregates are sub-classified into three categories on the basis of shape, size, and degree of distinctness and durability, referred as types, classes and grades of soil structure, respectively.

6.3.1. Types of soil structure

The four principal types of soil structure based on shape of the aggregates and their arrangement in the soil profile are platy, block-like, prism-like and spheroidal. Plate-like structure has relatively thin, flat horizontal aggregates or plates or leaflets. These plates are generally formed as a result of soil forming processes, may be inherited from parent material or are formed due to compaction of fine-textured soil by heavy machinery. They may be found in both surface and subsurface horizons. Blocky aggregates are irregular in shape, six-faced with their three dimensions more or less equal in size. Blocky aggregates are of two sub-types, i.e., angular blocky (when blocks' corners are not rounded but have sharp edges) and sub-angular blocky (if aggregates have rounded corners). These are usually found in B horizon.

Prism-like structures are characterized by vertically oriented aggregates or pillars which are longer vertically compared to their width. Two sub-types of prism-like structure are prismatic and columnar. When prisms have angular edges and flat clean cut tops, these are called as prismatic. When tops and sides of prisms are rounded like columns, these are designated as columnar. Both prism like aggregates are associated with swelling types of clay minerals and are most common in sub-surface horizons of arid and semi-arid region soils. The soils with spherical or rounded aggregates are placed in spheroidal category and are further sub-divided into granular (with relatively less porous peds) and crumb (when granules are porous) sub-types. These are generally common in surface soils or in A-horizons, mostly those high in organic matter.

6.3.2. Genesis of soil structure

The causes and mechanisms of formation of the aggregates are known as the genesis of soil structure. The development of stable aggregates or peds in soil takes place due to flocculation of fine soil particles by lowering of negative charge by polyvalent cations and stabilization of these by cementation with adhesive substances. Soil aggregates are formed during soil formation under the influence of alternate wetting and drying, freezing and thawing, vegetation, burrowing animals, earthworms, fungi, organic matter, nature of adsorbed cations or other disruptive forces. Aggregates are formed as a result of swelling and shrinkage due to wetting and drying of soil clod. For instance a soil mass swells due to wetting or freezing and then shrinks as a result of drying or thawing, cracks or lines of weakness are formed due to uneven expansion and contraction. The soil mass between cracks is stabilized by cementing agents.

Flocculation is a pre-requisite but not a sufficient condition for aggregation. Flocculation occurs by the adsorption of divalent (e.g., Ca^{++} and Mg^{++}) and trivalent (e.g., Al^{+++}) cations and / or by high solute concentrations. The polyvalent cations effectively neutralize negative charges on the soil particles and form bridges between clay particles that bring particles close together in small floccules. Double layer is compressed at high solute concentration and its repulsive effect is lessened and individual clay particles join each other by short-range attractive forces, called van der Waals forces, to form floccules. Then floccules are stabilized by cementing agents to form peds or aggregates.

Plants, animals, and the microbial community produce cementing agents that help bind the aggregates together. Bacteria decompose plant residues and produce polysaccharides and other organic glues. Plant roots, particularly root hairs, and fungal hyphae secrete sticky polysaccharides and other organic compounds that bind together soil particles and very small-sized aggregates. The mycorrhizae exude a sticky protein, called glomalin, which is very effective as a stabilizing agent. In many cases, raindrops are the major cause of the dispersion of soil aggregates. The aggregates cemented with iron and aluminum hydroxides are very stable and their structural degradation is least common even after intense rains in these soils.

6.3.3. Soil structure and its relationship with soil tillage and tilth

Good soil structure is an important feature of soil tilth. Tilth refers to the physical condition of the soil in relation to plant growth. Tillage has both beneficial and harmful effects on aggregation. If tillage is performed at optimum soil wetness level, its short-term effect is positive. Tillage implements break the clod, loosen the soil, increase water infiltration and reduce water run-off. When surface soil loses its structure and nutrients, inversion by tillage may bring aggregated and relatively more fertile subsoil to the surface which improves the soil tilth.

Over longer periods of time, tillage operations may have negative effects on soil structure. Plowing at very high or low soil water levels may be detrimental to soil tilth. Frequent use of heavy equipment may break aggregates and compact the soil surface. Continued cultivation and other tillage operations generally decrease stability of soil aggregates due to increase in decomposition of organic matter by exposing it to environmental factors. Tillage operations may also produce plow pan, if plowing is carried-out continuously at same depth with the same implement.

6.3.4. Importance of soil structure

Aggregation is a highly desirable state for soils because it greatly influences aeration, porosity and pore-size distribution, bulk density, heat transfer, transport and retention of water, root growth and penetration, microbial activity, and susceptibility of the soil to wind and water erosion. The formation and maintenance of stable aggregates are the most desirable characteristics for good soil tilth. Soil structure affects all plant growth factors, thus has a great agricultural significance, particularly at critical stages of seed germination and seedling establishment.

Soil structure is an important criterion used in studying soil profiles and classifying soil. It also influences infiltration of water in soil. For example, granular and single-grain soils have rapid infiltration, blocky and prismatic type soils have moderate, and platy and massive soils have slow infiltration. Erodibility of soil decreases with the increase in stability of the soil structure. Assessment of size distribution of peds, proportion aggregated and strength of soil aggregates is important for determining both the porosity and pore-size distribution of a soil. The extent and nature of aggregation modifies the influence of soil texture on crop growth due to change in pore-size distribution.

6.4. Soil Density

6.4.1. Particle density

Particle density is defined as the mass of oven-dry soil per unit volume of solid fraction or total soil volume excluding pore-spaces. It is an intrinsic property of soil and is same as the specific gravity of a solid substance. Particle density (ρ_p) is expressed as kilograms per cubic meter (kg m^{-3}) or mega grams per cubic meter (Mg m^{-3}) which is equal to grams per cubic centimeters (g cm^{-3}). Particle density is determined by the proportion of organic and mineral fractions and specific gravity of these particles. Most mineral soils have a particle density usually equal to about 2.65 Mg m^{-3}, which is an average density of both inorganic and organic particles. Factors affecting particle density are chemical composition and crystal structure of soil minerals and proportion of soil organic matter in the soil. It is a static property and is not affected by texture, structure, pore-space or any other property of soil. The ρ_p has no significance in plant growth. It is determined by pycnometer method.

6.4.2. Bulk density

Bulk density is defined as mass of oven-dry soil per unit bulk volume of soil including pore-spaces. It is expressed as kg m^{-3} (SI unit) or Mg m^{-3} (derived SI unit) or g cm^{-3} (old units). Bulk density (ρ_b) is generally determined by core-method. Core sampler is used to obtain an undisturbed soil sample of known volume and mass is determined after drying the sample in an oven at 105 °C and cooling in a desiccator. If soil is sandy or stony, then the simplest and best procedure is excavation method. A smoothed hole of 10 cm diameter and 10 cm depth is dug with a spatula through a 10 cm diameter hole of a metallic template placed on the soil surface. Total soil volume is determined by lining the hole with very thin plastic sheet and filling it with a measured volume of water up to base of the template. The ρ_b can also be determined by clod method. The volume of the wax coated clod is determined by weighing it first in air, and then while immersed it in water, making use of Archimedes' principle (Blake and Hartge 1986).

6.4.3. Factors affecting bulk density

Soil bulk density decreases with an increase in pore-space due to increase in the value of denominator, i.e. volume of bulk soil. Thus, any factor that influences pore-space, will also affects bulk density of soil. Factors affecting bulk density are soil texture, structure and its type, organic matter content, soil compaction, depth in the soil profile, nature of crops and soil management practices. Bulk density generally decreases with fineness of texture, increase in aggregation of soil and spheroidal type of structure, increase in organic matter content, addition of crop residue and farm manures to the soil. It increases with increase in soil profile depth and compaction, intensive cultivation, long-term tillage, repeated trips by heavy machinery and uncontrolled traffic.

6.4.4. Relationship of soil bulk density and root growth

Bulk density is a dynamic soil property varying with space and time. It is used to determine volumetric water contents, porosity and total mass of a volume of soil too large to weigh. It indicates the looseness or compactness of a given soil. Roots of field crops are hindered in soils with very high bulk density due to increase in soil resistance to root penetration and proliferation, slow movement of water and air, poor aeration and accumulation of toxic gases. Root growth is inhibited by soil compaction or higher soil strength and decrease in pore-size; all of these are affected by bulk density. Hence, these factors are taken into account to determine the influence of bulk density on root growth and it penetration in soil.

6.5. Pore-Space

Pore-space is the volume percentage of the soil volume not occupied by solid particles but is occupied by water and/or air. It is also called porosity which is defined as a ratio of volume of pores or voids per unit bulk volume of soil (volume of solid + volume of pores). Equation used to compute porosity or pore-space is based on the definitions for bulk density and particle density, is given below:

Total porosity = 1 - (bulk density / particle density)

Bulk density is the main soil property that influences pore-space because denominator (particle density) value commonly used is 2.65 Mg m^{-3}. Nonetheless, it does not give any idea about pore-size distribution which is more important from plant growth point of view.

Factors influencing porosity are essentially the same as that affecting soil bulk density. Total pore-space decreases with increase in soil bulk density, compaction, soil profile depth and cultivation. It generally decreases in surface soil due to more aggregation as a result of relatively higher organic matter and lack of overburden than subsoil.

6.5.1. Pore-size distribution

The volume-based percentage of various sizes of pores of the bulk volume in a soil is called pore-size distribution. Classification of pores on the basis of size is somewhat arbitrary. Based on their effective diameter, soil pores are generally grouped by size into micropores (< 0.03 mm), mesopores (0.03 to 0.08 mm) and macropores (> 0.08 mm). Micropores are generally present as intra-aggregate spaces, in which water and air movement is slow and are dominant in fine-textured soils. Larger micropores (effective diameter 0.005 to 0.03 mm) can accommodate most bacteria and root hairs, and plants can use water held in these pores. Mesopores can accommodate root hairs and fungi, retain water after drainage and transmit water by capillary rise. Water and air movement, water and nutrient retention in these pores lie in between macropores and micropores.

Macropores are commonly present as inter-aggregate spaces and voids between sand grains in coarse-textured soils. These can accommodate plant roots and certain tiny animals, and have rapid air and water movements. Macropores formed by plant roots, earthworms and other organisms are called biopores. They are more important in clayey soils and may be continuous up to one meter length or more.

6.5.2. Relationship of pore-space and bulk density

An inverse relationship exists between porosity and soil bulk density. Dry mass and volume of soil solids do not vary in the method used to calculate bulk density. Any factor that influences total porosity also effect bulk density of soil. The volume of pore-space is included in the denominator of the bulk density formula, thus as the value of total porosity decreases, soil bulk density increases.

Pore-size distribution is very important in determining water holding capacity, drainage, aeration and root penetration. Thus, knowledge about pore-size distribution has great agricultural significance than just knowing total porosity of the soil. The balance between various sizes of the pores is affected by soil texture, aggregation, organic matter contents, compaction and soil depth. Pore-size is enhanced from micropores to macropores by increase in sand, organic matter and aggregation in soil.

6.6. Soil Consistence

Soil consistence may be defined as the resistance of soil material to rupture and deformation or its degree of cohesion and adhesion at various levels of water contents. Soil consistence is the only soil physical property which has significance in agriculture and relevant to engineering uses. The term soil consistency is used by soil scientists for determining its suitability for tillage and traffic by estimating resistance to rupture. It is determined by crushing the soil clod between thumb and fore-finger or between hands or crushing under foot. The consistence is described at dry, moist and wet soil water content levels. The friable soils are easily tilled or excavated and term is more important from crop growth point of view. When moist soil clod breaks into aggregates under slight force between thumb and fore-finger without difficulty it is called friable. To puddle the soil for rice planting, plastic consistency is the optimum condition.

Factors affecting consistence are soil water content, soil texture, type of clay, specific surface area, soil structure and organic matter content. Soil consistency increases with decrease in water level, increase in clay content along with expanding type of clay and by puddling of soil.

Soil consistency is a term used by soil engineers to describe the interaction of forces of cohesion and adhesion within a soil material as expressed by the relative ease with which soil can be crushed or deformed at various soil water levels. It is determined by the soil's resistance to penetration of blunt end of a lead pencil or a thumbnail. Consistence and consistency provide valuable facts to guide decisions regarding loading and manipulation of soils.

6.7. Soil Color

Soil color is most obvious feature of soil and is an important criterion in soil classification and interpretation. It gives valuable information about other properties and conditions of the soil. It is determined by comparing the soil color to Munsell color charts and soil color description or nomenclature is standardized. Soil color notation is divided into three parts, namely hue, value and chroma. Hue is the portion of visible spectrum or 'rainbow' color and is related to the dominant wave-length of the light. Hue changes in units of 2.5 from 2.5 to 10 with 5.0 used as midpoint of each hue. As numerical number increases, wavelength decreases, i.e., less red. Hues commonly used for soils are: 5.0R, 7.5R, 10R, 2.5YR, 5.0YR, 7.5YR, 10.0YR, 2.5Y and 5.0Y.

Value is a measure of the relative darkness or whiteness of the color and is related to the amount of reflected light. It ranges between 0 for absolute black (all light absorbed) to 10 for absolute white (all light reflected).

Chroma is a measure of the relative purity or strength of spectral color and is related to the range of wavelengths reflected. It increases as greyness decreases and color is more brilliant as grayness decreases. Chroma subdivision ranges from zero (neutral gray) to 10 (brilliance) to 20 for pure colors which do not exist in soil.

The color designation for soil horizon is written in the order of hue, space, value, virgule and chroma, e.g., 10YR 5/4. In this example, color is dark red, 5 is value and 4 is chroma. Major factors that influence the soil color are its carbonates contents such as calcite, its water content, its organic matter content and the presence and oxidation states of iron and manganese oxides.

6.7.1. Effect of color on plant growth

Color has indirect influence on plant growth. Dark colored soils are generally warmer than light colored soils because they absorb more heat than do light colored ones. Due to greater amount of heat energy available, dark colored dry faster than light colored soils. Thus, colored surface affects soil temperature and water and indirectly soil structure, microbial activity and plant growth. However, dark colored soils with high humus contents may not be warmer because they also mostly hold more water and wetter soils require relatively larger quantities of heat than drier soils to raise their temperature. Productivity potential of these soils is higher due to more organic matter contents even though they are not warmer.

6.8. Soil Temperature

Soil temperature greatly influences the quality of soil as habitat for plants and microorganisms. Soil temperature influences soil aeration generally, through its stimulation effect on plant growth and on the rates of biochemical reactions. These interrelations are more important in water saturated or poorly aerated soils.

6.8.1. Soil temperature

Heat is a form of kinetic energy and level or index of heat is called temperature which is measured in degree Centigrade or degree Fahrenheit or Kelvin. Major factors affecting soil surface temperature are angle at which sun rays strike soil surface, latitude, altitude, season, time of the day, direction and aspect of slope of land, clouds, fog, soil color, its water content and soil surface covered by vegetation, snow or crop residues. As most of the solar radiations striking perpendicular or 90^0 to soil surface are absorbed by the soil, thus soil temperature is higher near equator, at sea level, during summer season and at noon. Soil temperature is also high when sky is clear; soil surface has no cover and dark colored, and has less water contents. Increase in water contents of dry soil increases its specific heat capacity, thus a wet soil will warm up much more slowly than a dry soil.

Solar radiation, convection, conduction and latent heat transfer are four mechanisms responsible for heat transport in soil. Out of these four mechanisms, conduction and latent heat convection are most important processes of heat transport into soil. Solar radiation is the short-wave radiation emitted from the sun in the form of electromagnetic waves through empty space and is the main source of energy for heating at or near the soil surface. Convection or the mass flow of heat is the process in which heat carrying particles actually moves from one place to another. It is associated with liquid and gas flow, for example with ocean currents and sensible heat, respectively. The sensible heat or convective heat flux represents the vertical transport of warm air from the soil surface to the atmosphere during day time and towards soil surface at night time.

Heat transmitted generally through solids by internal molecular motion without transfer of material particles is called conduction and is the most important mechanism for subsurface heat transport in soils. Latent heat transfer is convective heat transport associated with vapor flow in soil through heat absorption during evaporation at one place and release of heat during condensation at another place. Soil water resists significant changes in soil temperature due to its high specific heat capacity and evaporation in which high heat energy is required. The amount of heat required to raise temperature of one kg of water by one Kelvin is called specific heat and is expressed in J kg^{-1}.

6.8.2. Soil temperature management

Human ability to modify soil temperature is limited. Soil temperature must be between 4 – 10 °C for wheat, 10 – 29 °C for maize and 27 – 33 °C for cotton to get maximum seed germination. Even relatively small changes in soil temperature may have significant effects on seed germination and plant growth. Temperature of the soil surface can be modified by keeping some cover or mulch on the soil surface, controlling soil water contents through irrigation and drainage, sprinkling water on high-value plants to prevent frost damage and heat stress, growing vegetation, contoured and ridge planting, and by tillage practices.

The use of clear plastic mulch in cold season increases soil temperature by producing greenhouse effect. It permits production of high-value crops (like vegetables and strawberry) to take benefit of the high prices in early season markets. Vegetation lowers the soil temperature by means of intercepting considerable portion of incoming radiation and using the heat energy for evapo-transpiration and photosynthesis. Planting seeds on ridges increase temperature in cold season due to positioning them to receive more direct sunlight along with rapid drying of the soil. Organic and plant residues left on the soil surface decrease conduction into and out of soil, causing warmer temperature in winter season and cooler temperature during summer season. These plant residues tend to minimize day and night fluctuations by working as insulating agents and do not allow the soil to become either too hot during summer and too cold during winter season.

6.8.3. Significance of soil temperature in plant growth

Soil temperature is one of the most critical factors which affect important physical, chemical and biological processes in soils and plants. If soil temperature is too low or too high for optimal plant growth, productivity of crops and other vegetation is often decreased, resulting in temperature dependent growth and yield patterns.

Soil temperature greatly influences seed germination, seedling emergence and development, root growth, plant growth and maturity of crops. It also affects microbial activity, decomposition and mineralization of organic matter, and nutrient and water uptake by roots. Water and nutrient uptake is decreased below optimum rates at both very high and low temperatures. All these factors are very important in plant growth and yield of crops.

6.9. Soil Aeration

Soil aeration refers to the process by which soil air is exchanged by air from the atmosphere and to the transport of gases through the pore-spaces filled with air. Gases move both into and out of soil and the rate of such gas exchanges depends largely on the volume of macro-pores and their continuity, soil water contents and drainage within the soil.

The volume of a soil not occupied by soil solids or water is the gaseous phase of soil called soil air. In a well-aerated soil, the soil air is similar in composition to the atmospheric air above the soil. Atmospheric air contains 79 % nitrogen, 20.97 % oxygen and 0.03 % carbon dioxide and 20-90 % water vapors. Soil air contains 79 % nitrogen, less oxygen, more carbon dioxide and water vapors (95-99 %) than atmospheric air but the sum of oxygen and carbon dioxide gases remains the same in soil and atmospheric air. Factors affecting composition of soil air are soil texture, structure, temperature, compaction, water contents, organic matter, soil depth, microbial and plant root activity. Soil properties influence the air-filled porosity and permeability of soil. More the plant roots and microbial activity more shall be the production of CO_2 in soil.

Diffusion and mass flow are the two mechanisms responsible for the exchange of gases between soil and atmosphere. However, diffusion is considered the primary mechanism of gaseous exchange. The partial pressure gradient of carbon dioxide or oxygen in soil or atmosphere above is important for diffusion and total pressure gradient is important in mass flow. The partial pressure of oxygen in mixture of gases is the pressure oxygen gas exert if it was present alone in the soil air. Net movement of oxygen is generally towards the soil air because the oxygen content is lesser in soil than in the atmospheric air. On the contrary, CO_2 moves in the opposite direction as its partial pressure is generally higher in the soil air.

Rainfall and irrigation water are also help in the renewal of soil air. Irrigation accounts for 5% and rainfall constitute about 6 to 9 % of the normal aeration. Rainwater displaces soil air from the soil pores and these are refilled with atmospheric air during percolation of water. Rainwater is also enriched by dissolved oxygen which is exchanged with the soil phase. One cm of rain over an area of one hectare adds 100,000 liters of rainwater that contains 4339 g of oxygen at 20C^o (Saha, 2004).

6.9.1. Measurement of soil aeration

The aeration status of a soil can be characterized by measuring: a) aeration or air-filled porosity; b) composition of soil air; c) the oxygen diffusion rate (ODR); and d) the oxidation-reduction (redox) potential. An early method to measure soil aeration is determining air-filled porosity which is expressed as a fraction or percentage of the bulk volume of soil that is occupied by air at any given time or specified water content. Aeration porosity is either calculated by subtracting volumetric water content from total porosity or measured directly with an air pycnometer. A typical poorly aerated soil has aeration porosity value of less than 10 %.

Measurement of the composition of soil air is the traditional approach and is a static indicator of soil aeration because soil gases are measured from gas samples collected from the soil profile. It gives more information whenever O_2 concentration of soil air decreases significantly lower than the atmospheric air. The ODR determines the rate at which oxygen of soil air can be replenished by diffusion when it is used by respiring micro-organisms or plant roots. The growth of most plant roots ceases when ODR value is less than $20x10^{-4}$ g m^{-2} $minute^{-1}$ and values greater than 40×10^{-4} g m^{-2} $minute^{-1}$ are considered sufficient for optimum growth of most plants. This method is most useful in fine-textured soils and for comparing ODR levels at different soil depths.

Redox potential (Eh) is the electrical potential of a soil created due to tendency of the chemical elements in it to donate or acquire electrons. It is usually measured in millivolts (mV) or volts (V). Soil Eh depends both on its pH and the presence of electron acceptor. Oxygen gas (O_2) rapidly accepts electrons from other elements. In poorly aerated soils, Eh value is less than 350 mV and oxygen disappears at Eh value of about 300 mV. Well-aerated soils have Eh values of more than 400 mV. Oxidized form of important chemical elements such as nitrate, sulfate, carbon dioxide, ferric iron and tetravalent manganese (Mn^{4+}) are dominant in well-aerated soils.

6.9.2. Effect of aeration on plant growth

Two life sustaining gases in soil air are CO_2 and O_2 since these are essential for photosynthesis and root respiration, respectively. Carbon dioxide is a primary greenhouse gas because it traps reflecting back long-wave radiation and prevents it from escaping into the outer space. Human related CO_2 emissions are responsible for its increase in atmosphere occurred since industrial revolution. This high concentration of CO_2 in atmosphere may be partially responsible in global warming.

Plants roots and microbes need O_2 for respiration which is needed for life and growth. When ODR is too low and the redox values drops, plant roots cannot respire and their growth slows down or stops. Except rice, cultivated crop plants grow best in well-aerated or oxidized soils. Rice plants can move O_2 internally through large diameter pores from their tops in atmosphere to their roots. If free O_2 concentration is too low, some elements or ions become the electron acceptor. In poorly aerated soils, many organic acids are formed which may be toxic to higher plants and to decomposing organism. The nitrates are denitrified and N_2 and N_2O gases formed are escaped to atmosphere, thus expensive N fertilizer input is wasted. Sulfate is reduced to sulfide and CO_2 is converted to methane. Under anaerobic (lack of free O_2) condition, the rate of organic matter decomposition is much slower than under aerobic condition. In the presence of free O_2 (aerobic condition), glycolysis plus respiration releases about 19 times more energy (stored in ATP bonds, than anaerobic breakdown.

6.10. Soil Tillage, Tilth and Plant Growth

Tillage may be referred as the mechanical manipulation of soil aimed at improving soil conditions necessary for crop production. Major purposes of tillage include preparation of seed bed, eradication of weeds, destroying of soil crust, conserving water as well as soil, incorporating plant residues and farm manure into the soil, and creating optimum compactness for good soil-seed contact plus root penetration. Tilth is also a result of soil tillage and is discussed in Section 1.3.3. The soil must be friable and well aggregated, permitting free movement of water as well as air and easy cultivation in addition to planting crops.

6.11. Soil Health

Soil health and soil quality considerations are becoming popular worldwide. Soil quality is the capacity of soil to function within ecosystems according to the land use for sustaining productivity, maintaining environmental quality and improving plant and animal health. The National Resource and Conservation Service of USA have made it more meaningful by adding inherent and dynamic soil quality to its basic definition. The inherent soil quality is defined as the aspects of soil quality related to a soils natural composition and properties influenced by the factors and processes of soil formation in the absence of human influence. However, the dynamic soil quality relates to the soil properties which are result of soil use and management over time.

6.11.1. Indicators of soil health

There is dire need of establishment of the protocol for soil health assessment that may be cost effective and affordable, easy to understand and executed by the laboratory staff. There are number of soil health indicators that can be used for assessing soil quality in comparison to their effectiveness for reflecting true soil health status and its correlation with crop production. The soil health concept is an integrated approach comprising soil physical, chemical and biological parameters to address the soil constraints effectively and to enhance farmers' profitability (Gugino et al. 2009).

These can be divided in to three categories:

20) *Physical*: The most important physical parameters include bulk density, macro-and meso-porosity, available water capacity, penetration resistance,

saturated hydraulic conductivity, wet aggregate stability and water infiltration rate of soil.

21) *Chemical parameters* comprised of pH, CEC, nitrate nitrogen, potassium, phosphorus, calcium, magnesium, iron, zinc and copper contents.
22) *Biological parameters* include soil organic matter content, potential mineralizeable nitrogen, particulate organic matter, active carbon, root bioassay and nematode population.

Most important physical parameters will be discussed here. The water stability of soil aggregates measures the extent to which soil aggregates resist the separation from one another through subsequent rain (or in water) and mechanical manipulation. Water content is important in structural stability and is an important factor in determining the degree to which particular mechanical forces will cause structural breakdown.

Available water capacity or plant available water refers to the difference in the amount of water retained in the soil at the field capacity and permanent wilting percentage or at the soil water potential values between -10 to -30 kPa and -1500 kPa. Available water capacity of the soil generally increases as the fineness of its texture or organic matter content increases. The amount of water retained in a soil one to three days after irrigation or rain or after downward movement of water by gravity become negligible, is called field capacity (θ_{fc}). Water potential at θ_{fc} is usually in the range of -10 to -30 kPa depending upon soil texture. Field capacity gives upper limit of water useful to plants but it is inexactly defined as its value changes with soil texture, structure, type of clay mineral, organic matter contents, depth of initial wetting and impeding layers. When plants growing in a soil do not regain their turgor and remain wilted when placed under humid conditions, the soil water content at this stage is called the permanent wilting point and for most plants it is the amount of water held by the soil when the water potential is -1500 kPa. Under this condition plants are not dead but will die if water is not provided.

The ease with which a standard cone penetrometer can be pushed into the soil at given water content is called penetration resistance. It is generally recorded in units of force, required to push the soil penetrometer into the soil. This is just a correlation measurement which is important in seedling emergence as well as establishment, root growth in addition to penetration and in tillage. Factors affecting penetration resistance are soil water content, its texture, organic matter content, type of exchangeable cations and clay minerals, bulk density and soil compaction. For a given bulk density, soil penetration resistance decreases with increase in water contents.

Hydraulic conductivity of a saturated soil is a measure of ease or ability of a soil to transmit water through its pores or it is an expression of readiness with which water flows through a soil in response to a given hydraulic gradient. It is the proportionality constant in Darcy's law and is calculated by dividing water flux by water potential gradient. Factors affecting saturated hydraulic conductivity are pore-size distribution, soil texture, structure, bulk density, soil compaction, water temperature, nature of exchangeable cations and organic matter contents. It increases with increase in number of macropores, coarseness of texture and with aggregation, whereas presence of high amount of exchangeable sodium, compaction of a soil and decrease in water temperature decrease saturated hydraulic conductivity of a soil.

The rate at which free water enters downward through the soil surface is called infiltration rate and is expressed in units of m s^{-1}. It is generally measured with a double ring infiltrometer in which one metal cylinder is smaller in diameter than the outer one. The depth of water in the inner cylinder is recorded at given time intervals. The infiltration rate is highest when water first enters the dry soil, generally decreases rapidly at first and then become constant at large-time. The hydraulic conductivity is approximately equal to the constant rate of infiltration. Factors affecting infiltration rate are surface vegetation, initial soil water contents, texture and structure, size of pores, type of clay mineral, soil compaction, development of crust or seal and irrigation water quality.

6.11.2. Soil health, environmental quality and its impact on crop growth

Soil health refers to soil quality and its suitability for crop growth and production. A healthy soil must possess some special qualities like good soil tilth and sufficient soil depth with good profile development, so that plant roots can perform their function properly. Sufficient supply of nutrients is necessary for maintaining nutrient balance within the system but excess of these may lead to leaching, ground water pollution, eutrophication, greenhouse gas losses and toxicity to soil microbes and plant life. In a healthy soil, the population of the plant pathogens and insect pests must be controlled; otherwise these will compete with the crops for nutrients making the crops poor in health. Healthy plants are better able to protect themselves against attacks of diseases, like human beings, due to their more effective and better resistance system. Well-aggregated soil can tolerate raindrop impact and hold optimal water content due to its high water holding capacity and suitable pore-size distribution. Water may cause the deterioration of aggregation in two ways. First, hydration causes a disruption of the aggregate through the processes of swelling and the exploding of entrapped air. Second, the impact of falling raindrops on exposed soil can break up the aggregates. The dispersed particles are then carried into the soil pores, causing decrease in porosity. Intense rains destroy the structure of the top few centimeters of soil to form a dense, impervious surface known as a crust or seal.

Various beneficial microbial populations are also essential feature of good soil health. They have significant role in organic matter decomposition, mineralization, nutrient cycling, structure stability, porosity, suppression of plants pests and thus maintaining good soils health.

Healthy soil must be free of toxic metals and chemicals that may damage crop growth and production. Healthy soils are managed by adsorbing heavy metals and making them less toxic for crops and save groundwater from pollution. Water pollution may damage human health and especially of the children who have weak immunity system and may suffer from diseases like blue babies (methemoglobinemia) due to high NO_3 contents in drinking water and paralysis due to Cr metal. A healthy and well-structured soil can tolerate adverse events and climate like erosion by wind and water, extreme drought etc.

6.12. Soil Carbon Sequestration

Carbon sequestration refers to the process of capture and storage of the carbon by transfer of atmospheric CO_2 into terrestrial (i.e., soil and biota) and geologic (i.e., deep strata and oceanic) pools and subsequent long-term storage, as a result it is not released back into the atmosphere. Soil carbon sequestration refers to transferring atmospheric carbon to the soil carbon pool in the soil profile either through humification of biomass residue and/or formation of secondary carbonates.

6.12.1. Soil carbon sequestration and soil health

The principal aims of soil carbon sequestration are to improve water holding capacity, enhancing biodiversity and sustain crop productivity to achieve food security for rapidly increasing population of the world. Restoration and protection of soil organic carbon above critical level improves soil quality and consequently results in increased crop production per unit input of water, land area and energy. This strategy is very important, particularly for developing countries like Pakistan having low organic carbon soils and intensive cropping pattern. Organic carbon level in soil varies with climatic zones, tillage practices, cropping pattern and rate of fertilizer application. Adoption of recommended management practices enhance and sustain biomass production and improve soil quality. Soil health can be sustained by sequestering more carbon by conservation tillage, efficient nutrient management, reduced grazing, erosion control by using cover crops and restoring degraded or desertified soils.

6.12.2. Soil carbon sequestration and environmental quality

Carbon is being lost as carbon dioxide and methane gases and is sources of pollution. Human activities are adding more CO_2 in the atmosphere ever since industrial revolution. It is the primary greenhouse gas and due to its increasing concentration, there is increase in global temperature. Due to this, water level in oceans is increasing posing threat to the cities close to them. Soil carbon sequestration is a natural process that removes carbon dioxide from the atmosphere and stores it on long-term basis in the soil profile. It is one of the most efficient and cost-effective means of off-setting fossil fuel emissions to decrease the rate of CO_2 enrichment in the atmosphere. The soil carbon sequestration process can defer or mitigate global warming and provide economic gains, environmental benefits and agro-biodiversity.

6.13. Conclusion

In this chapter, all the physical, chemical and biological aspects related to the soil quality have been addressed. The soil quality has been considered as integrated approach by covering all three aspects of soil quality to give more sound and practicable information's for agriculture and environmental sustainability.

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