Soil Properties

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Abstract

Nepalese soils are developed dominantly from micaceous parent materials such as phyllites, schists, gneisses, and granites; thus, most of the soil contains a higher proportion of mica. Nepalese soils are mostly friable in hills and mountains because of the continuous use of organic inputs such as farmyard manure and compost, while soils are hard and compacted in the Terai region because of the continuous use of machinery and less use of organic inputs. Soils in hills exhibit higher soil plasticity but the intensity of soil plasticity decreases in lower belts where erosion deposits prevail and most of the soils are sandy in nature. The soils of Nepal also show wide variability in chemical properties, and thereby respond differently to the same crop across ecological zones and soil types. In general, the soils of Nepal are acidic in nature. About 53% of soils are in the acidic range, while 33% are neutral, and 13% are in the alkaline range. In general, soils in hills and mountains are richer in major plant nutrients and organic matter than soils in the Terai region. However, the content of micronutrients such as zinc, boron, and molybdenum are low. Overall, soil nutrients are being mined throughout the nation, with the fastest decline in eastern areas and in the Terai region. Soil erosion, imbalanced use of fertilizers, low or no use of organic inputs, and adoption of intensive cropping systems are some of the major causes for the decline in soil nutrients.

Keywords

Biofertilizers • Nepal • Organic matter • Soil acidity • Soil fertility

8.1 Introduction

Soil properties are comprised of physical, chemical, and biological properties. These properties affect various soil characteristics including soil production capacity and determine suitability for crop husbandry practices. Soils are living, complex, and dynamic in nature, and their properties vary across time and space as they are composed of minerals, organic matter, and air. Soil is the medium for the natural growth of plants and is usually characterized by different horizons governed by various processes of soil formation such as addition, losses, transformation, and translocation. Soil characteristics such as water holding capacity, density, moisture content, drainage, aeration, compactness, retention of plant nutrients vis-à-vis their availability to plants are related to both the physical and chemical properties of soil. Chemical properties are mostly the result of parent material composition. Soil biological properties are often active when organic matter in the soil is adequate. Chemical properties are rich when the soil has enough nutrients derived from its parent materials. Hence, all soil properties are equally important for sustaining crop production.

8.2 Soil Physical Properties

Soil properties are determined by five major factors: parent material, climate, organism, topography, and time. The role of the above-mentioned factors is expressed in the equation developed by V. V. Dokuchaev:

$$S = f(Cl, O, R, P, T) \qquad (8.1)$$

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where S = soil or any soil property, Cl = climate, O = organism (e.g., vegetation), R = relief or topography, P = parent material, and T = time.

To simplify and understand soil physical properties, we need to understand the constituents of soil as the solid, liquid, and air phases. The solid phase is usually characterized by the physical properties of soil texture and soil structure.

8.2.1 Soil Constituents and Their Relationship

Ideally, by volume soil consists of 45% inorganic matter (solid), 5% organic matter (solid), 25% water (liquid), and 25% air. The percentage of air and water varies with the state of soils. When soil is saturated, all porous space is occupied by water, whereas in dry soils most pores would be occupied by air. Organic matter is composed of dead and living microorganisms and plants whereas inorganic matter is composed of minerals. The mineral particles are of different sizes and include sand, silt, and clay. These particles are the foundational materials for soil.

Some of the terminology commonly used in soil physical properties are as follows:

(a) Bulk density: The mass of oven-dried solid per unit volume of soil. It has a unit of g cm^{-3}, and it usually ranges from 0.8 to 2.0 g cm^{-3}.

(b) Particle density: The mass of oven-dried soil particles per unit volume of soil particles. A value of 2.65 g cm^{-3} is used if the true value of particle density is not known.

(c) Porosity: The volume of porous space per unit volume of soil. It is unitless but expressed as a percentage. The relationship between the three is as follows:

$$\text{Porosity} = 1 - \frac{Bulk\ Density}{Particle\ Density} \tag{8.2}$$

(d) Gravimetric water content (GWC): The mass of water per unit of oven-dried soil. It is mass versus mass. For mineral soil, the value ranges from 0 to 0.6 g g^{-1}.

(e) Volumetric water content (VWC): The volume of water per unit of oven-dried soil. It is volume vs volume. Similarly, the value for volumetric water content ranges from 0 to 0.5 cm^3 cm^{-3}.

If the gravimetric water content is known, then the volumetric water content can be calculated based on soil bulk density and the density of water using Eq. (8.3)

$$\text{VWC} = \text{GWC} * \frac{soil\ bulk\ density}{density\ of\ water} \tag{8.3}$$

(f) Available soil water: The water content available between field capacity (water managed by irrigation scheduling) and the permanent wilting point (water unavailable to the plant) is called available soil water.

Soil Texture

The relative proportions of sand, silt, and clay in the soil are referred to as soil texture. There are various ways to identify soil texture, for example, soil textural angel calculator, feel method, texture-based on size, sedimentation method, etc. The properties of soil texture are important in determining the soil's physical, chemical, and biological properties.

Nepalese soils are developed from micaceous parent materials such as phyllytes, schists, gneisses, granites, and others, and most of the soil contains a higher proportion of mica. Loam and sandy loam are the most dominant soil textures in both hills and alluvial terraces (Carson 1992). Many studies show that the different textures in different parts of Nepal, but dominated by loam soil. A study conducted in a watershed in the Likhu river, a tributary of the Trisuli river in the northern Kathmandu valley, shows that soil textures in the soil surface are dominated by loam, silty loam, and silty clay loam (Gardner and Gerrard 2003). Similarly, another study in the Pokhare Khola watershed shows sandy loam soil (Shrestha et al. 2007). Another study from two different sal (*Shorea robusta*) forests found that the soil was sandy loam (60.12–50.58% sand, 28.59–35.24% silt, and 11.12–22.41% clay) (Paudel and Sah 2003). In 50 soil samples collected at 0–20 cm depth in the rice fields at the National Rice Research Program at Hardinath, Dhanusha, the soil texture was dominated by loam types (Khadka et al. 2017b), with sand ranging from 5.1 to 67.6%, silt ranging from 20.5 to 64.5%, and clay ranging from 9.6 to 40.8%. The soil texture for 81 soil samples collected at Regional Agricultural Research Station in Tarahara, Sunsari in 2016 were observed to be loam (34%), clay loam (10%), sandy loam (4%), silt loam (32%), and silty clay loam (20%), respectively (Khadka et al. 2017a). Likewise, 76 soil samples collected at Regional Agricultural Research Station found that most soil texture belongs to the silt loam category, with sand ranging from 15.6 to 41.1%, silt ranging from 40.8 to 63.2%, and clay ranging from 14.8 to 26.2% (Khadka et al. 2018).

Soil Structure

Soil structure is the arrangement of individual particles of sand, silt, and clay into a larger soil particle. Smaller particles are called peds, which are influenced by the interactions of soil particles. The soil structure assists in the movement of air and water in soil (Brady et al. 2008).

Regarding the soils in Nepal, the structure is different in various studies. For example, soils at the National Rice Research Program at Hardinath, Dhanusha, and Regional

Agricultural Research Station in Tarahara, Sunsari had sub-angular blocky structures (Khadka et al. 2017a). Likewise, soils at Regional Agricultural Research Station in Parwanipur, Bara had an angular blocky structure (Khadka et al. 2018). These and the studies above show that there is variability in soil structure and texture within different parts of Nepal.

Soil Consistency

The properties of soil such as friability, plasticity, stickiness, ease or resistance to compression, and others are all related to the moisture and organic matter content of the soil and form some examples of soil consistency. In general, the soils are mostly friable in hills and mountains because of the continuous use of organic inputs such as farmyard manure (FYM) and compost (SSD 2016,2017). However, in the Tarai region where the use of organic inputs is low, hard consistency dominates. The Tarai areas are intensively cultivated and farmers use relatively higher amounts of chemical fertilizers compared to the hill and mountain regions. Application of organic manure in Tarai soils is low, and even crop stubbles from fields are removed to feed animals or as fuel wood.

Soil Plasticity

Plasticity is exhibited by soil containing more than 15% clay and is exhibited over a range of moisture contents referred to as plasticity limits. It is also considered the upper limit of moisture content for tillage operation for most crops excluding rice. Soils in the hills exhibit higher plasticity but the intensity of plasticity decreases in lower belts where erosion deposits prevail and most of the soils are sandy in nature.

Soil Color

Due to the temperate climate, the weathering of the rocks and minerals is slow in higher altitudes (mountains), whereas it is faster in the lower altitudes of the Tarai region. In the same manner, soil color also ranges from brown and dark brown in high altitudes to yellowish to reddish-brown, olive-brown, and white to grayish brown in lower altitudes.

Nepalese farmers always consider black soil to be fertile and brownish-white soil to be unfertile. Even in red soil, the surface soil color changes to black or another color due to physical, chemical, and biological reactions, including organic matter. Because of organic matter, the application of other mineral fertilizers continues biological and chemical reactions that accelerate root decay and increase soil carbon stock in the rhizosphere (Angst et al. 2018).

Soils from the old river terraces known as *Tars* (flat land in the foothills with relatively warm micro-climate) in Nepal that drain to the rivers are red. The same soils when cultivated with seasonal irrigation, and the addition of organic matter gradually turns brown, reddish-brown, and/or yellowish-brown (Walker and Lin 2008). River silt with low organic matter added to cultivated fields changes the soil color to olive and olive-brown. Upland soils, when a sufficient amount of FYM or compost is added, look black. Though the topsoil remains black the subsequent soil horizon remains a mix of dark and brown (Kaiser and Guggenberger 2005). This is mainly due to the movement of humus and clay colloids leaching with the irrigation water. Nepalese Tar soils are very porous, and hence the colloidal particles leach down to the subsoil and even deep into the bottom horizon when there is water to move downwards. These soils have original reddish-brown color. In some conditions, a concretion of manganese oxide develops and is black (Ivarson and Heringa 1972; Zhang and Karathanasis 1997). Such cases are observed in some parts of Terai.

Waterlogged soils are saturated with the groundwater and gleyic condition developed where the soil color is gray to light gray (Motomura 1969; Rabenhorst 1990). This condition is common in most rice cultivated areas including large irrigation command areas of Nepal. In most seasonal irrigated rice fields, the topsoil is generally dark brown to brown and the subsoils are mostly light brown to olive-brown. This olive-brown color is mainly a result of the leaching of soil colloidal particles that are deposited in verticals and/or horizontal ped faces.

8.2.2 Physical Constraints in Nepalese Soils

Soil physical constraints generally refer to the physical degradation of soils, including structural degradation that hinders crop yield (Singh et al. 2014). These properties mainly consist of soil texture, soil erosion, bulk density, soil structure, soil sealing/crusting, soil temperature, water holding capacity, water infiltration capacity, and aeration. When these properties degrade, it is difficult to bring them back to favorable conditions (Sen 2003). The physical constraints of Nepalese soils should be grouped into two categories, as their setting and development differ.

Soil texture: The physical properties of soil play an important role in improving soil fertility. Hill soils are light and developed in phyllite, schists, and quartzite, and hence are coarse (Baumler and Zech 1994), whereas valley and Tarai soils are heavier (Pal et al. 2001; Srivastava et al. 1998). There are patches of calcite soils, along with valleys and foothills of colluvial deposits (Mücher et al. 2018). Glacial deposit soils in Nepal are mostly coarse and may be alkaline, as in the case of the soils of the Pokhara Valley. Light-textured soils are low in nutrient holding, water-holding, high water infiltration, and permeability (Ogban and Babalola 2003). Soil consisting of less than 10% clay particles is said to be light and sandy and have high water permeability; crop productivity of these soils is low (Singh et al. 2014). Tarai soils mostly contain a higher percentage of clay and are fertile. With the addition of 5–10 t ha^{-1} of well-decomposed, organic manure will help to increase water and nutrient-holding capacity in addition to other physical properties especially in the soils of the hills and mountains.

Soil erosion: Erosion is greater in the cultivated fields of Nepal and especially in upland conditions in the hills and mountains where soils are light and susceptible to both water and wind erosion. The eroded finer materials are deposited elsewhere, leaving a coarse skeleton on the surface and making poor-quality soil (Gardner and Gerrard 2003). When soil erosion takes place, soil particles are first detached from the soil aggregates in the surface soil, after which they are transported and the organic matter and other nutrients associated with these surface soil particles are lost. Thus, eroded soils are infertile and have low productivity (Gardner and Gerrard 2003; Schreier et al. 1994). There have been very few studies measuring soil loss from cultivated fields. Schreier et al (2000) reported the loss of up to 20 t ha^{-1} fertile soils annually. Sediment estimation on a watershed basis is 1–9 t ha^{-1} yr^{-1} as the result of erosion. Wind erosion is high in the High Mountain and Himalayan regions where wind speed is very high, though because agriculture production in this area is minimum its effects are not discussed in detail. Eroded sediments are deposited in the valleys and sometimes mix with landslide debris. Landslides and heavy floods deposit sediment-loaded debris in the valleys and plain areas, which are also poor in fertility (Karki 1986; Shrestha 1985).

Soil sealing/crust: Soil crusting generally occurs when there is heavy rain. When raindrops hit the soil surface, fine particles are splashed and transported away leaving the coarse particles on the surface. As a result of raindrops continuously hitting the surface, the aggregates are disintegrated into small particles and in some cases are puddled. After a day or night of rain, the small soil particles form a layer that is hard, brittle, and friable. This layer can range from a fraction of an inch up to 1.5 in thick. In Nepal, growers generally notice this type of crust in dry seedbed nurseries for rice. Even in wet rice nurseries after puddling, the water is cut off and the finer particles are left to settle; in a day or two, the puddled layer forms crust that splits to form cracks. When this seal or crust on the soil surface is formed, water infiltration is lower and it is harder for seeds to germinate. Likewise, soil crust increases bulk density and decreases the porosity percentage resulting in lower root proliferation. The amount of crust depends on the raindrops and the intensity of the rain, which increases soil compactness and bulk density (Bajracharya and Lal). Soil crust formed due to beating by raindrops is prone to soil erosion (Morin and Van Winkel 1996), and the formation of soil crust depends on soil texture, where light textures are prone to crusting (Gabriels et al. 1997; Lui et al. 1996). Since Nepalese soils are light in texture and raindrop intensity is high (Gardner and Gerrard 2003; Gilmour et al. 1987), they are more susceptible to crusting and soil erosion.

Soil temperature: Soil temperature is latitude dependent, as tropical soils are always warmer than temperate soil. Soils on north-facing slopes in the southern hemisphere and soils on south-facing slopes in the northern hemisphere are warmer than soils on southern slopes in the southern hemisphere and soils on northern slopes in the northern hemisphere (McLaren and Cameron 1996). As it is in the northern hemisphere, the soil temperature regime of Nepal is the mesic type. However, other soil temperature regimes can be found in Nepal, such as cryic and frigid in the High Himalayan region and thermic in the Tarai region. In high mountains where snowfall is dominant during winter, seeds are sown during October and remain inside the soil without germination, though these seeds begin germinating soon after the snow starts melting because of the rise in soil temperature. The snow acts as insulation and the soil temperature rises, ultimately favoring seed germination and rapid crop growth.

Soil structure: Soil structure indicates soil pores and soil bulk density (BD). There are several types of soil structure such as crumb and granular, which are the best for infiltration and air movement and thus the best for seed germination. The subangular blocky structure is a medium type of structure that is available in fertile soils. The angular blocky structure is somewhat harder and generally available in the harder plow pan of rice soils. It indicates that this structure is compact, with higher BD and a lower porosity percentage, and that it is unfavorable for root growth. Mohammed et al. (2020) argues that the climate controls structure formation as warmer climate is humid and lead to finer soil aggregates whereas in temperate regions soil structures are harder. The columnar and prismatic structures are much harder and are found in salt-affected and sodic soils (Horn et al. 1964). These soils have higher BD, low porosity, low infiltration, and low permeability. Plant roots do not grow deeper and concentrate only on the surface soil, which is made favorable by intercultural operation. Because Nepalese farmers in the hills and river valleys apply a sufficient amount of organic manure to their field crops, the structure of surface soil is mostly granular or crumb. Due to its highly porous nature and the organic acids formed during the degradation of organic matter leaching down to the subsurface horizon, the subsoil remains as a subangular blocky structure.

Leaching of organic acids from the top horizon favors biological activities and mineralization of nutrients and promotes plant biomass. Paddy soils may have some disturbances in their soil structure that are generally hard, as puddling for rice cultivation destroys soil structure but rotating soybean into the cropping system has been found to improve soil structure (Cass et al. 1994) because the legume roots can break the plow pan and extract nutrients from subsoil while biologically fixing nitrogen. Therefore, scientists advise farmers to include legumes in their crop rotation. Chickpeas, lentils, field peas, and lathyrus are cultivated in a rotation with rice. As the Tarai soils of Nepal are lower in organic matter, the surface soil structure is getting more compact.

Bulk density (BD): Bulk density is the ratio of mass by volume and is generally measured in g cm^{-3}. For good crop growth, the BD should be between 1.0 and 1.5 g cm^{-3}. If the BD is below 1.0 g cm^{-3}, there will not be any anchorage for the plant to stand, whereas above 1.5 g cm^{-3} there will be lower aeration for the proper growth of the plant roots. Meki et al. (2013) argued that conventional tillage increased soil bulk density, whereas no-tillage treatment lowered bulk density while increasing biomass. Begum et al. (2013) pointed out that there is a seasonal difference in bulk density in the hills of Nepal, indicating 1.19 g cm^{-3} in the pre-monsoon season and 1.31 g cm^{-3} in the post-monsoon season, which is optimum bulk density in agricultural soils. Regmi and Zoebisch (2004) showed a slight difference between khet (rice cultivated lowland) soils at 1.38 g cm^{-3} and upland soils at 1.23 g cm^{-3}. Both studies show that bulk density in the hills and mountains is favorable for cultivation of crops. Bulk density in the Tarai soil is a bit higher than in the mountains. Gami et al. (2001) reported that a control plot where no organic manure was added showed 1.69 g cm^{-3} and plots where only fertilizer was applied showed 1.49 g cm^{-3}, whereas other organic manure-treated soils showed 1.40 g cm^{-3}. Similar results (1.69 g cm^{-3} from control plots) were also reported from the Indo-Gangetic plain of India (Gangwar et al. 2006). Both the results are from experimental plots, though in farmers' fields the results can be slightly different.

Water-holding capacity and water-infiltration capacity: The infiltration of water refers to the movement of water through micropores. If the micropores are sealed water movement is also sealed (Ela et al. 1992). In some upland soils in Nepal, there are more micropores, and water moves through the soil at higher speeds; sometimes this movement is so rapid that it is unmeasurable. In irrigated river valleys soil contains a higher amount of silt and fewer micropores result in low water infiltration. No-till cultivation practices in rice-wheat cropping systems in the plains region lower water infiltration more than tillage practices (Jat et al. 2013). Water infiltration in the hills and mountain soils is normally high; the soil moisture index of different physiographic regions is depicted in Fig. 8.1.

Organic matter and clay content in soils are the two main factors affecting water-holding capacity (WHC). When there is high organic matter and clay content in the soil, WHC will also be high (Khaleel et al. 1981; Vengadaramana and Jashothan 2012). Similarly, clay content also increases as WHC increases (Lund 1959). Agvise (2020) showed examples of WHC under different soil textures, with sandy loam at 29.4%, loam at 85.0%, silt loam at 71.9%, and clay at 73.7%. The hill and mountain soils are rich in soil organic matter and hence WHC is high, whereas Terai soil, though low in organic matter, contains high silt and clay content, whereas WHC is also high.

Soil aeration: Soil aeration is related to compaction and bulk density, in addition to soil hydraulic properties, nutrient movement, and root respiration (Grable 1966). When the soil is fully saturated with water, plant roots cannot breathe and plants (with the exception of rice) turn yellow. In Nepal, this problem appears mostly in winter crops, especially wheat and lentils, due to unexpected heavy winter rains. Some vegetable crops such as tomatoes also suffer from heavy rain and flooding conditions. Farmers generally drain water as quickly as they can or wait for the rain to stop and apply urea fertilizer.

8.3 Soil Chemical Properties

Soils of Nepal show wide variability in chemical properties, and thereby respond differently to the same crop across ecological zones and soil types. Variation in topography, soil-forming parent materials, climatic conditions, soil management practices, and organic matter content are major factors that determine the variations in soil chemical properties. The soils of Nepal are acidic in nature (53% of soils are in the acidic range, 33% are neutral, and about 13% are alkaline). About 44% of soils are low in organic matter, 56% in nitrogen, 49% in potassium, and 42% in phosphorus. However, potassium content was high (68%) a decade ago but is also on a decreasing trend (Dawadi and Thapa 2015). Soil fertility status (i.e., the nutrient content in soils) is declining throughout the nation, with the most rapid decline taking place in eastern Nepal. Deficiencies of many nutrients have been observed in different patches that often limit crop production; therefore, improvements in plant nutrient

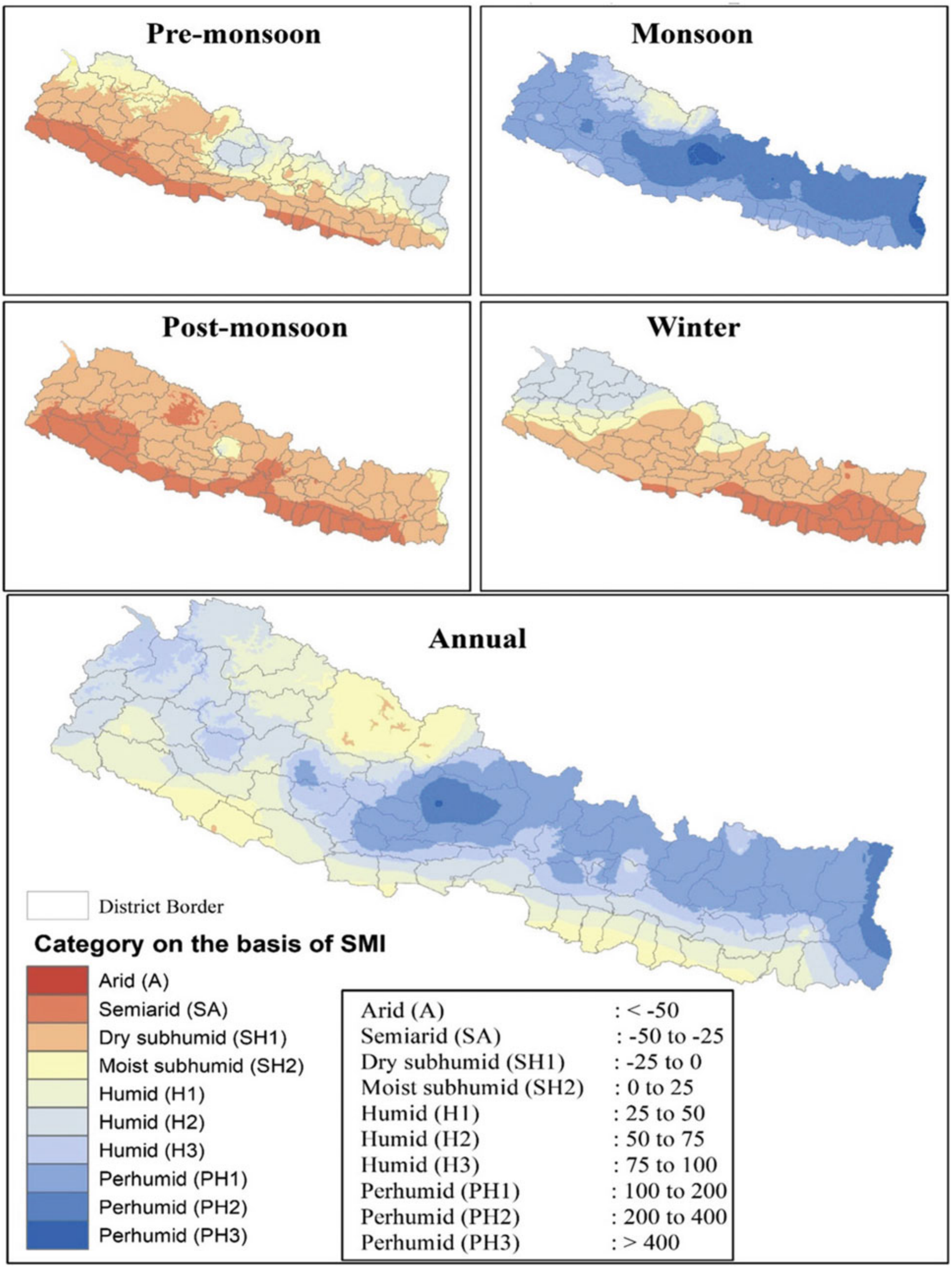

Fig. 8.1 Soil moisture index (SMI) variation in different seasons and physiographic regions of Nepal (maps re-drawn) (Talchabhadel et al. 2019; written permission granted from Talchabhadel on 08 February 2021)

management systems are crucial for enhancing soil fertility and crop productivity. In Nepal, studies on other chemical properties such as cation exchange capacity, base saturation, electrical conductivity, and the status of heavy metals are lacking.

8.3.1 Soil Acidity

Soil pH (activity of H^+ and OH^- ions) is an important soil chemical property that determines the availability of soil microbial activities and nutrient availability to plants. All acid soils contain hydrogen ions, and the strength of the acid depends on the degree of ionization (i.e., the release of hydrogen ions) of the acid. The more hydrogen ions are held by the exchange complex of soil in relation to the basic ions (Ca, Mg, K, and Na), the greater the soil acidity. In Nepal, soil acidification is one of the major challenges for the sustainable improvement of soil fertility.

Status of soil pH in Nepal

Out of 16,585 soil samples analyzed by the Soil Management Directorate (SMD), Department of Agriculture, Ministry of Agriculture and Cooperative, Government of Nepal, about 53% of samples were acidic, followed by 34% neutral and 13% alkaline (SMD, DoA 2013). In general, soils of eastern Nepal are relatively more acidic than soils in the central and western parts of the country (DOA/STSS 1999, Fig. 8.2). Similarly, soils in the hill and mountain regions are more acidic compared to soils in the Tarai region. Soil analyses over the past decade show that soil acidity is increasing due to faulty soil management practices, including imbalanced use of chemical fertilizers (more urea, but lower or no use of phosphorous, potassium or other secondary and micronutrients), lack of awareness among farmers in managing acidic soils, and a lack of availability of agricultural lime on the market. Soil pH determines soil quality as described in Table 8.1 Soil quality rating in Nepal based on soil pH value.

Causes of Soil Acidity in Nepal

Rainfall and irrigation

Rainfall contributes to soil's acidity due to the leaching of basic cations. Water (H_2O) combines with carbon dioxide (CO_2) to form a weak acid: carbonic acid (H_2CO_2). The weak acid ionizes, releasing hydrogen (H^+) and bicarbonate (HCO_2). The released hydrogen ions replace the calcium ions held by soil colloids, causing the soil to become acidic. The displaced calcium (Ca^{++}) ions combine with the bicarbonate ions to form calcium bicarbonate, which, being soluble, is leached from the soil. The net effect is increased soil acidity. High-rainfall areas, especially in eastern Nepal (1,000–2,000 mm), are associated with acidic soils due to increased leaching of base cations (Ca^{2+}, Mg^{2+}, K^+, etc.) (Lucas et al. 2011).

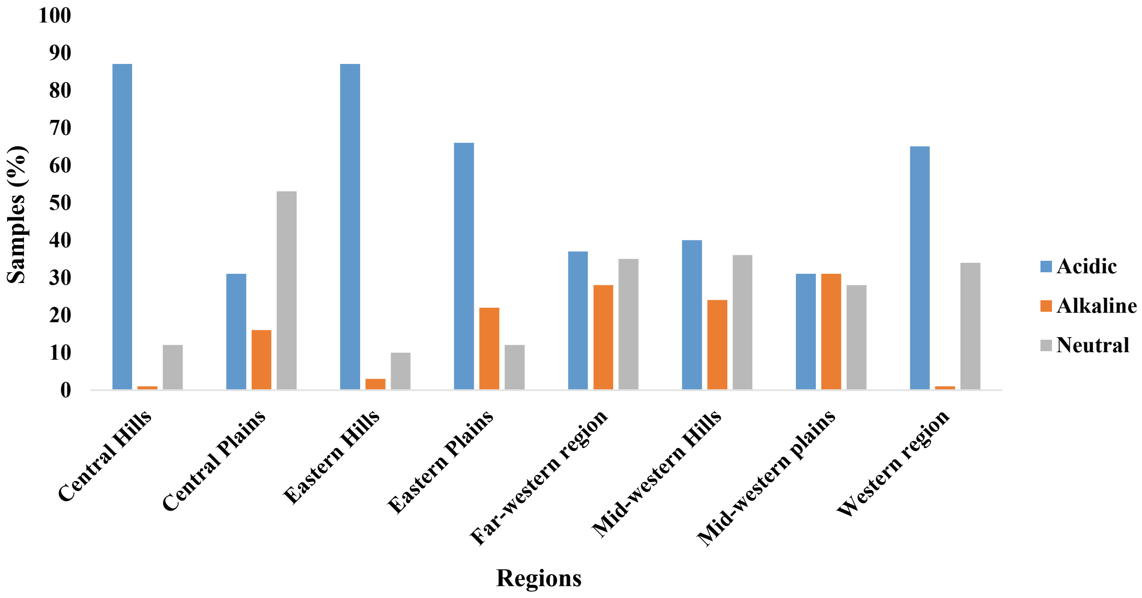

Fig. 8.2 Soil pH status of different regions of Nepal (SMD, DoA 2013, n = 6442)

Table 8.1 Soil quality rating in Nepal based on soil pH value

Soil pH	Ranking value	Soil quality rating
<4, >8.5	0.2	Very poor
4.1–4.9	0.4	Poor
5–5.9	0.6	Fair
6–6.4, 7.6–8.5	0.8	Good
6.5–7.5	1.0	Best

Based on DoA/STSS (1999), Sitaula et al. (2004)

Acid rain

Rain with a pH value less than five is referred to as acid rain. The pH of acid rain is usually between 4 and 4.5 but can sometimes be as low as two. It is formed due to the emission of oxides of nitrogen, sulfur, and carbon from industry, automobiles, and other sources. Acid rain serves as a source of soil acidity, especially in soil with low buffering capacity. The soil in industrial and high-density traffic areas has generally developed acidic soil due to acid rain.

$$SO_2 + {}^1\!/_2O_2 + H_2O \rightarrow H_2SO_4 \rightarrow SO_4^{2-} + 2H^+$$

Limited studies on acid rain in Nepal have been conducted and as there has been little major industry in Nepal there has been a minimal chance of the country experiencing acid rain. However, it is possible that heavy traffic and low-quality transport fuel have aggravated acid rain especially in the Kathmandu Valley (Shrestha and Malla 1996).

Parent material

The soils of Nepal have developed on Himalayan residuum and alluvium derived from shale, sandstone, and siltstone and have a low buffering capacity (FAO 2006). These weakly buffered minerals facilitate the development of soil acidity, particularly in the mid-hill region.

Imbalanced use of inorganic fertilizers

The continuous use of nitrogenous fertilizers such as urea and ammonium sulfate, particularly when they are used in an imbalanced way, increases soil acidity. The higher the nitrogen fertilization rate, the greater the soil acidification. As ammonium is converted to nitrate in the soil (nitrification), H ions are released. For each kilogram of nitrogen as ammonium, it takes approximately 1.8 kg of pure calcium carbonate to neutralize the residual acidity. Also, the nitrate that is provided or formed can combine with basic cations such as calcium, magnesium, and potassium and leach from the topsoil into the subsoil. As these bases are removed and replaced by H ions, soils become more acidic. Most farmers in Nepal apply only urea as a chemical source of fertilizer, which has an acidic residual effect. The imbalanced use of chemical fertilizer over the long term has increased soil acidity, particularly in the Tarai region where less organic manure is applied.

Carson (1992) reported that factors that contribute to increased soil acidity in hilly areas are the increasing use of nitrogenous fertilizer and the government reforestation program's emphasis on pine tree plantations, both of which have increased acidity in hilly areas. Nevertheless, less acidic soil in agricultural lands compared to forestland suggest that fertilizer-driven acidification is not a major problem in the mountains of Nepal. Per capita fertilizer use in Nepal is very low compared to other south Asian countries. Previous studies revealed that soil acidity induced by fertilizer application was observed only after 10 years of continuous fertilizer use in experimental plots at Bhairahawa (Carson 1992).

Plants

Crop selection is also responsible for creating soil acidity. For example, leguminous crops such as soybeans, alfalfa, and clover tend to take up more cations in proportion to anions. This causes H ions to be released from plant roots to maintain the electrochemical balance within their tissues. The result is net soil acidification. While this process is not well documented in Nepal, continuous legume systems in hilly areas are common practice in places where farmers have no options due to marginal irrigation or lack of irrigation. Similarly, the effects of Sal trees on soil acidification have not been extensively reported, though coniferous species (e.g., Chir-pine) are known for their contribution to soil acidification by releasing organic acids from their roots and by absorbing base cations (Rigueiro-Rodriguez et al. 2012).

Soil Acidity Management Practices in Nepal

In general, soil pH can be raised by adding lime (calcium/magnesium carbonate). The amount to add depends on the cation exchange capacity (nutrient-holding capacity) of the soil, which is based on its clay content and buffering capacity. Soil higher in clay will have a higher cation exchange capacity and requires more materials to raise the soil pH.

Karki and Dacayo (1990) recommended 6–9 t ha^{-1} of lime on various soils, whereas Adhikari et al. (2007) recommended 4 t ha^{-1} lime for western mid-hill regions under maize-based cropping systems. However, considering the remoteness and lack of supportive logistics especially in the Hill regions, there exists the need for alternative methods for correcting soil acidity. For example selection of local and exotic germplasms of maize, wheat, upland rice, soybean, and black gram suitable for acidic environments. Tripathi (2000) recommended applying lime in combination with compost or organic manure. The author also recommended 2 t ha^{-1} lime for maize and wheat that would increase yield up to 35% compared to a non-limed plot. Thus, this is one area in nutrient management that needs to be studied systematically. In addition to liming other management options to overcome soil acidity problems have also been reported; for example, diversified cropping was reported to improve residue quality and quantity by supplying a variety of above- and below-ground biomass and residue inputs, which has the potential to improve soil pH and soil fertility (Umiker et al. 2009). Increasing soil organic matter in soil can increase soil pH and its buffering capacity in highly acidic soil (Umiker et al. 2009).

The government of Nepal has recommended lime requirements based on soil pH value for different soil texture groups and geographic regions (Table 8.2). Although lime recommendations are made by the government, they are rarely practiced by farmers due to the lack of availability of lime on the market. Moreover, the use of lime is limited by its high transport cost, lack of farmers' awareness, lack of soil testing facilities, and other factors.

8.3.2 Organic Matter Content in Nepalese Soil

Organic matter is the core constituent of agricultural soils. Organic matter incorporation improves soil fertility resulting in a good crop harvest. Improved Soil Organic Matter (SOM) forms the basis of soil health and is required for improved soil health and fertility. Due to the unbalanced use of chemical fertilizer, lower use of organic inputs, and a poor strategy of organic matter management, SOM in Nepalese agricultural lands have deteriorated substantially, affecting the soil's productive capacity. The Agriculture Development Strategy (ADS), a 20 year-long term vision of the Nepal government, has set a target of enhancing SOM from the current 1.96% to 4% by 2035. The ADS includes the promotion of integrated soil fertility management (ISFM) and improvement of agricultural practices such as crop rotation, incorporation of crop residue (including direct incorporation and composting), and integrated crop nutrition as the main strategies for achieving 4% SOM. Recent soil analyses carried out by the Land Use Project in the Terai region show a mean organic matter content of 2.24% (minimum 0.3% to a maximum of 7.3%), though this analysis included forest soil as well. The highest OM is found particularly in forest soils, not agricultural soils, where soils were found to have mostly medium organic matter content. In many parts of Nepal, soil organic matter content is less than 2%, and in some areas, it is below 1%, especially in cultivated Terai soils. Soil organic C content is generally higher in higher elevation soil due to cooler climate and slow decomposition, but with shallow soil depth. Soil organic matter depends on the land use and season. Agricultural land has low SOM due to tillage and a poor management system. In areas where sustainable soil management practices are followed, higher SOM was observed compared to soil where conventional practices were followed.

Soil organic matter varies with ecological zones and land-use types. It is higher in grasslands and forests (e.g., in the mountains) and lower in agricultural lands (e.g., in Tarai) as shown in Fig. 8.3. The eastern part of the Tarai region has lower SOM compared to the western part of the Tarai, while the Mid-Hills and Higher Hills have similar ranges across the country that are higher than the Tarai region.

Soil organic matter shows a declining trend, and the causes behind this vary between agro-ecological zones and management practices. The use of FYM has decreased due to a decrease in livestock population and the incorporation of crop residue. Moreover, in Tarai dung cakes are used as fuel for cooking. Intensive and repetitive monocropping, the shift from traditional to conventional agriculture, and mechanization are some of the leading factors contributing to the decreased organic matter in agricultural soils. Moreover, abandoning traditional agro-ecological practices such as the retention of crop residue, fallow cropping, crop rotation, and intercropping coupled with the unbalanced use of chemical fertilizer and unsustainable practices adopted by commercialized agriculture has further resulted in the loss of soil organic matter (MoALD and Practical Action 2020).

8.3.3 Status of Plant Nutrients in Nepalese Soils

The status of plant nutrients in Nepalese soils varies widely between agro-ecological zones, cropping systems, and crop management practices. In general, both macro- and micronutrients are on a declining trend because of increasing crop intensification, decreased use of organic inputs, and removal of crop residues from agricultural land, among other factors. With the intensification of the cropping system, farmers are removing crop residue from their fields and allowing shorter fallow periods, while at the same time use of other organic inputs such as FYM, compost, green manure, and cover crops are declining, resulting in the mining of plant nutrients from soils.

Table 8.2 Recommended lime requirements by the Government of Nepal based on soil type and physiographic region

Soil pH	Hills (t ha^{-1})			Terai (t ha^{-1})		
	Sandy loam	Loam	Clay loam	Sandy loam	Loam	Clay loam
6.4	0.30	0.40	0.48	0.16	0.28	0.44
6.3	0.58	0.80	0.96	0.30	0.48	0.88
6.2	0.86	1.20	1.44	0.46	0.68	1.28
6.1	1.16	1.56	1.96	0.60	0.88	1.72
6.0	1.42	1.84	2.40	0.76	1.04	2.12
5.9	1.70	2.20	2.92	0.90	1.24	2.56
5.8	1.94	2.56	3.32	1.04	1.44	2.92
5.7	2.16	2.84	3.76	1.16	1.64	3.32
5.6	2.38	3.16	4.16	1.28	1.80	3.68
5.5	2.60	3.40	4.60	1.40	2.00	4.00
5.4	2.80	3.76	5.04	1.52	2.20	4.40
5.3	3.00	4.08	5.48	1.62	2.36	4.76
5.2	3.20	4.36	5.88	1.72	2.52	5.08
5.1	3.38	4.56	6.28	1.82	2.72	5.40
5.0	3.52	4.80	6.68	1.92	2.84	5.72
4.9	3.68	5.04	7.04	2.02	3.00	6.04
4.8	3.82	5.24	7.48	2.12	3.16	6.32
4.7	3.98	5.44	7.80	2.22	3.32	6.60
4.6	4.10	5.60	8.12	2.30	3.48	6.80
4.5	4.20	5.80	8.40	2.40	3.60	7.00

Source Agriculture Information and Communication Center (AICC), Krishi Diary (2076), MoAD

Status of macronutrients

Among the primary (NPK) nutrients, Nitrogen (N) is the most limiting nutrient in Nepalese soils. However, the N content in soils varies widely across agro-ecological zones. Most Terai and eastern Mid-Hill soils have a total N content of less than 0.15%, while western Mid-Hill soils are rich in N (Fig. 8.4). This suggests that the Tarai plains and the eastern Mid-Hills require higher amounts of nitrogen fertilizers to achieve optimum crop yields, while in the western Mid-Hills and mountains the N requirement could be smaller compared to Terai soils.

Phosphorus content in soils also varies across agro-ecological zones. As with N content, the phosphorus content of most eastern Terai soils are lower than 55 kg P_2O_5 ha^{-1}, though it is higher than 55 kg P_2O_5 ha^{-1} in most western Terai soils (Fig. 8.5). Hill and mountain soils are richer in phosphorus compared to Terai soils. Different studies conducted by Nepal Agricultural Research Council (NARC) show that the soil phosphorus level is increasing in Nepal as most farmers use Diammonium Phosphate fertilizer to cultivate their crops.

Unlike their nitrogen content, Nepalese soils are rich in potassium. Although Terai soils have relatively lower potassium content compared to hill and mountain soils, the nutrient level falls within the medium range (110–280 kg K_2O ha^{-1}) (Fig. 8.6). As Nepalese soils are rich in potassium, most farmers do not use potassium fertilizers to cultivate their land. NARC has recommended a very low amount of potassium (10–50 kg K_2O ha^{-1}) as a maintenance dose. However, due to intensive crop cultivation coupled with residue removal from farmland and the lower use of organic inputs, potassium mining has begun in Nepalese soils (Ojha et al. 2021). A SMD report based on an analysis of 15,000–20,000 soil samples from different parts of the country shows rapid decline in potassium over the last two decades. So, Ojha et al. (2021) recommend increasing potassium content to 1.5–2 times for rice and 2–2.5 times for wheat to the current rate of potassium recommendation (30 kg K_2O) per hectare in rice–wheat cropping system of Nepal.

Information on available sulfur, calcium, and magnesium in Nepal is lacking. In Nepal, most analyses are conducted to determine soil pH, organic matter, nitrogen, phosphorous, and potassium. It is reported that soils from eastern Nepal contain lower amounts of calcium and magnesium (which is associated with higher rainfall) compared to western Nepal.

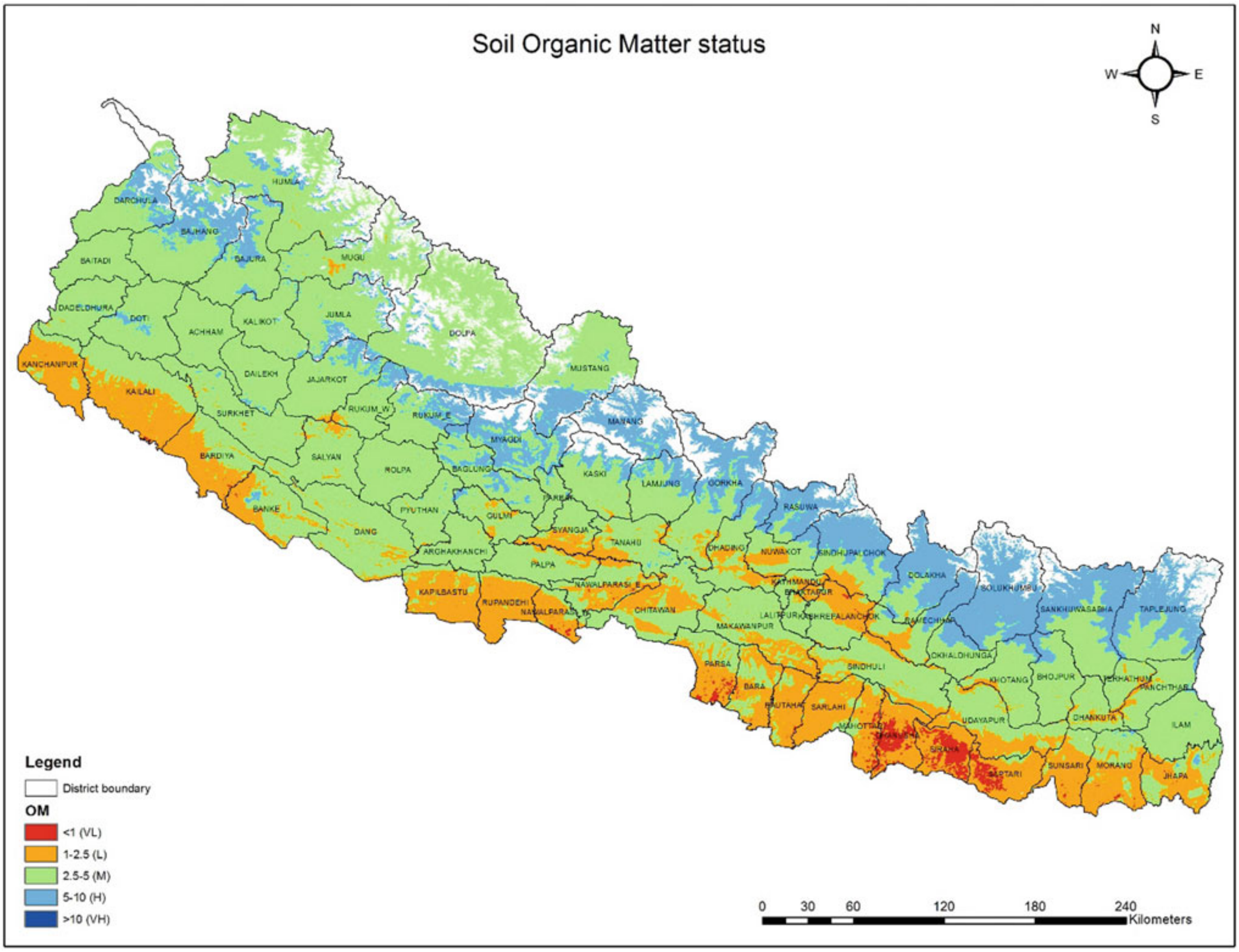

Fig. 8.3 Organic matter content in soils across different agro-ecological zones of Nepal (*Source* Digital soil map 2020, developed by feed the future Nepal seed and fertilizer project and NARC)

Status of micronutrients

Information on the status of soil micronutrients is limited in Nepal. Soil analyses for micronutrients were conducted mostly from NARC's research stations (Table 8.3). The reported analysis was not consistent with the analysis methods; thus, they could show wide variability. A review made by Bajracharya et al. (2007) shows that as with other primary and secondary nutrients, the content of micronutrients in soils was depleted as the addition of organic inputs in soil decreased with crop intensification. Moreover, there are no official recommendations for micronutrients; thus, farmers have limited awareness regarding their use. Some use of micronutrients such as Zn for rice and maize, B for vegetables, and Mo for cauliflower, has been acknowledged. Among the micronutrients, B, Zn, and Mo are deficient in Nepalese soils. Anderson (2007) reported that out of the total samples analyzed across the country based on different reports, proceedings, and articles, 80–90% of soil samples were deficient in B, 20–50% were deficient in Zn, and 10 to 15% were deficient in Mo, while the status of Cu, Fe, and Mn was not a problem.

8.4 Soil Biological Properties

Status of microbes in Nepalese soil

Soil microorganisms differ in type and number based on soil temperature, moisture, management practice, soil type, ecology, and other factors. Nepal has a diverse ecology and its altitude ranges from 60 m asl to the highest peak of the world, Mt. Everest, at 8848.86 m asl. Agriculture is practiced up to about 3500 m asl. The land area above 3500 m asl is used for grazing and pasture. Since microorganisms have a pivotal role in mineralizing soil nutrients and making

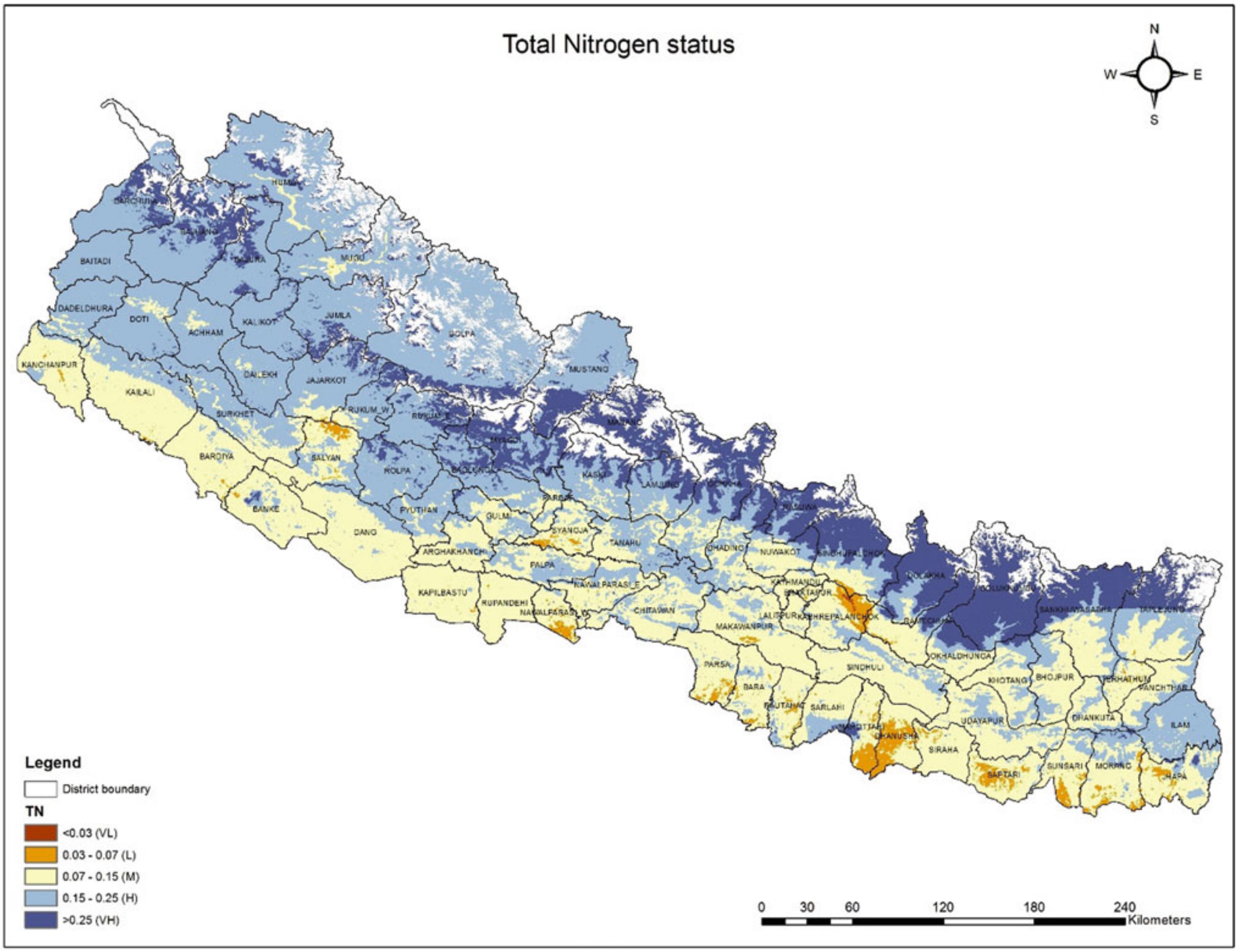

Fig. 8.4 Total nitrogen content (%) of soils across different agro-ecological zones of Nepal (*Source* Digital soil map 2020, developed by feed the future Nepal seed and fertilizer project and NARC)

them available to agricultural crops, it is necessary to study the diversity and population of soil microorganisms at varying altitudes so that the amount of nutrients to be applied can be substantially predicted.

Distribution of microbial diversity in different ecological zones of Nepal

Limited research has been carried out in Nepal with respect to microbial diversity in varying ecological zones. Studies carried out by NARC's Soil Science Division (SSD) in recent years showed that location and treatment have little influence on population and diversity, though a higher degree of fungal and bacterial population was observed in the Terai plains. The Mid hills and High Hills showed a similar level of the fungal and bacterial population. Different treatments of soil under long-term soil fertility trials have not shown a definite trend of the microbial population (SSD 2019).

Altitude is the major factor that has confounded effects on both biodiversity and soil physicochemical properties. High-altitude ecosystems are generally characterized by low temperature, variable precipitation, decreased atmospheric pressure, and soil nutrient stress, all of which have major impacts on biodiversity (Morán et al. 2013). The microbial population varies with varying soil ecology. The *Azotobacter* population was observed to be in higher order in Mid Hill soils compared to Mountain and Terai soils. However, the fungal population was higher in Tearai soil compared to the soil from the Mid and High Hills. This means that low altitudes have a larger fungal population. Different treatments of soil under long-term soil fertility trials have not shown definite trends related to microbial populations. Future studies should focus on microbial population

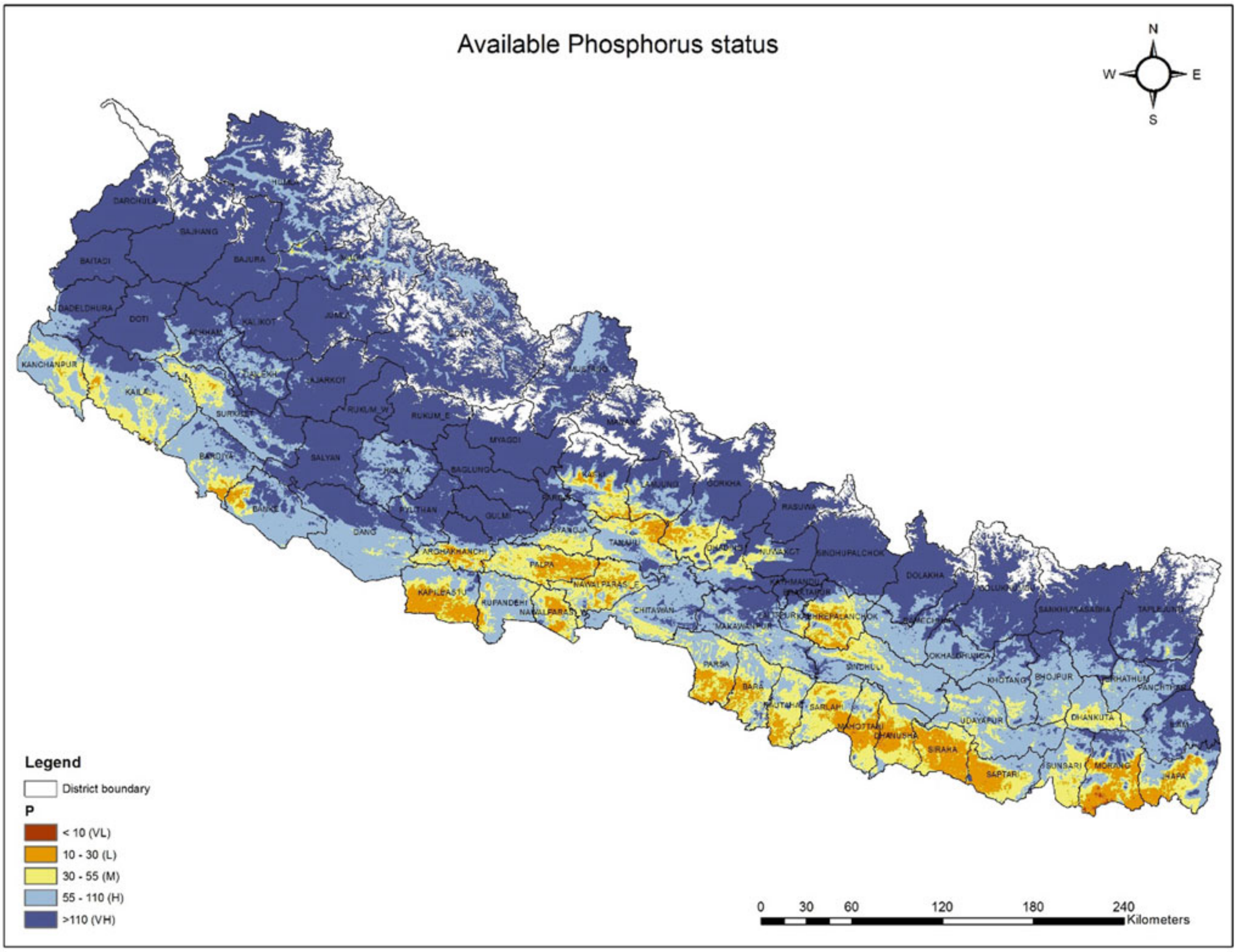

Fig. 8.5 Available phosphorus (kg P_2O_5 ha^{-1}) of soils across different agro-ecological zones of Nepal (*Source* Digital soil map 2020, developed by feed the future Nepal seed and fertilizer project and NARC)

dynamics under different soil management practices across different altitudes.

Agricultural Practices and Soil Biological Properties

Soil is a complex mixture of organic matter, water, air, minerals, and living things formed after the chemical disintegration of rock fragments. Soil quality is the interaction of physical, chemical, and biological properties for agricultural practices and other activities performed in the soil. The biological quality of soil involves a variety of factors occurring within the soil profile, at the surface, and above the ground that is associated with of derive from the living component of the soil ecosystem. This includes the diversity and species composition of soil organisms, namely meso- and macro-fauna, microorganisms, and flora (the types of plant, their root systems, and the vegetative litter produced at the soil surface). We discuss here how agricultural practices influence soil biological properties.

Effect on soil organic carbon stabilization and mineralization

The amount and quality of soil organic matter reflects the nature and abundance of soil flora and fauna and can be considered an indicator of biological soil property. Several studies on the status and dynamics of soil organic carbon (SOC) have been conducted; however, very limited research related to soil fauna and microbial activity has been carried out in Nepal. Bajracharya et al. (2004a) analyzed existing SOC data from the literature and concluded that as expected forest and shrubland soils had higher SOC contents in the top 30 cm; however, due to shallow soils and low density, forest soils had overall lower total OC stock than soils from

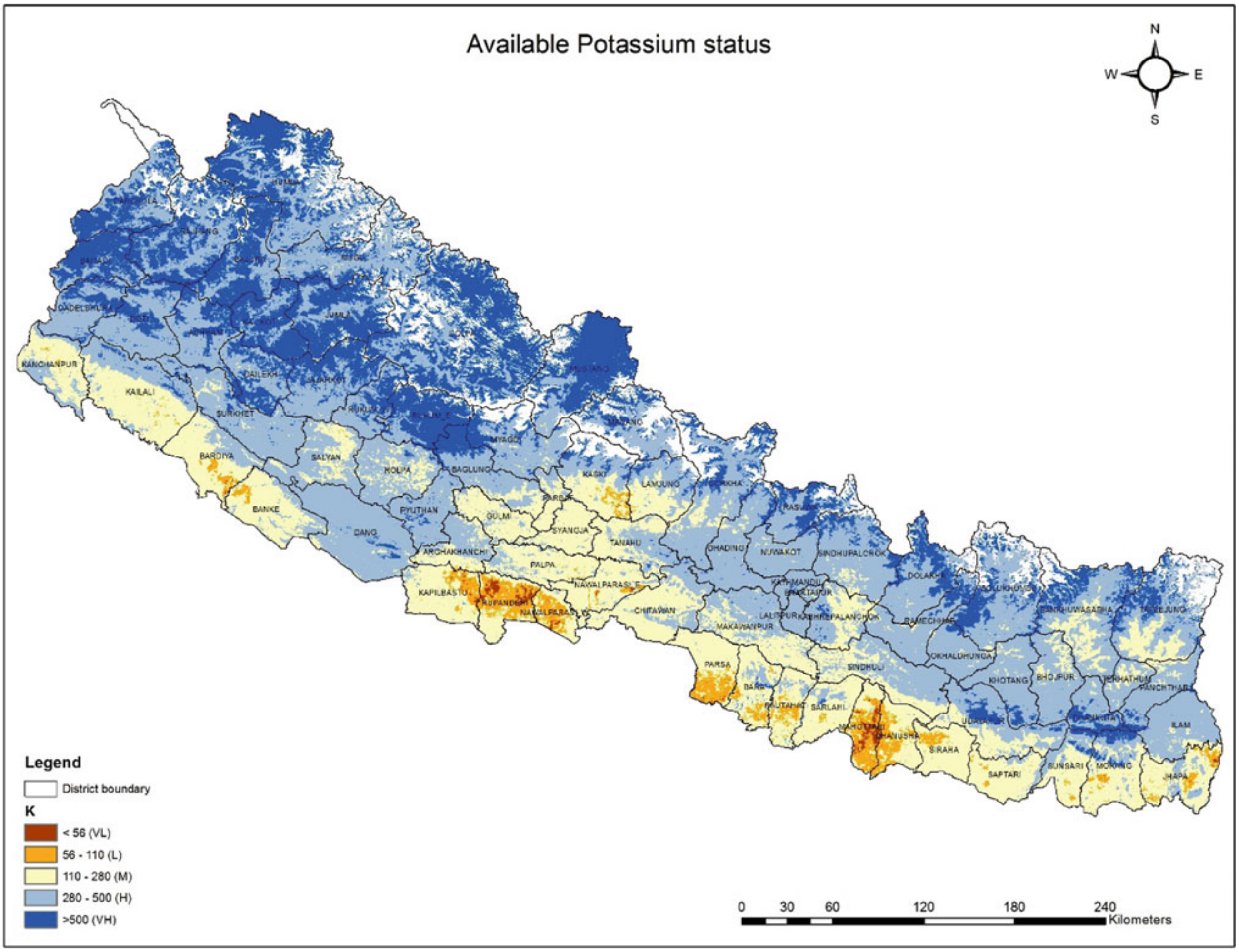

Fig. 8.6 Available potassium (kg K_2O ha^{-1}) of soils across different agro-ecological zones of Nepal (*Source* Digital soil map 2020, developed by feed the future Nepal seed and fertilizer project and NARC)

Table 8.3 Status of micronutrients in soils across different NARC research stations in Terai, Nepal

Micronutrients	Units		Research stations (sites)					
		Tarahara, Sunsari	Hardinath, Dhanusha	Belachapi, Dhanusha	Parwanipur, Bara	Chitwan	Bhairahawa, Rupandehi	Nepalganj, Banke
Boron (B)	mg kg^{-1}	0.08	0.37	0.56	0.59	0.46	0.23	1.13
Zinc (Zn)	mg kg^{-1}	0.35	0.83	0.54	0.51	0.55	2.94	1.82
Iron (Fe)	mg kg^{-1}	244.7	57.79	55.80	85.88	15.89	75.05	21.33
Molybdenum (Mo)	mg kg^{-1}	–	–	–	–	–	–	0.20
Cupper (Cu)	mg kg^{-1}	1.15	0.89	0.30	1.36	0.39	1.87	0.10
Manganese (Mn)	mg kg^{-1}	18.15	6.75	20.50	16.52	3.86	6.87	8.27
Source		Khadka et al. (2017a)	Khadka et al. (2017b)	Khadka et al. (2016)	Khadka et al. (2018)	Khadka et al. (2016)	Khadka et al. (2015)	Baral et al. (2020)

other land use types. While cultivation tends to reduce SOC contents of soils, practices such as mulching, minimum tillage, retention/addition of organic residue, and cover crops can all enhance productivity and reduce erosion losses. Concurrently, degraded forest and grazing lands were noted to be severely depleted in SOC (on the order of 0.1%). For agricultural soils, the SOC contents fell mostly between 1 and 3% in topsoil. Shrestha et al. (2007a,2007b) investigated SOC stocks and C sequestration in a Mid-Hill watershed in western Nepal and reported a significant influence of land use on SOC contents. Among the cultivated land use types, upland soil had higher SOC, while natural forests had the highest overall SOC stocks. A net loss of 29% of SOC stock in the uppermost 40 cm layer of soil was calculated due to changes in land use over the period from 1978 to 1996 (Shrestha et al. 2007).

Effect on microorganism population and diversity

Soil contains many micro- and macroflora and fauna. Soils contain about 8–15 t ha^{-1} of bacteria, fungi, protozoa, nematodes, earthworms, and arthropods (Brady and Weil 2012). A large number of bacteria exist in the soil, but due to their small size, they have smaller biomass. Actinomycetes are 10 times smaller in number than bacteria but larger in size so they have similar biomass in the soil (Hoorman and Islam 2010). Fungal population numbers are smaller but they dominate the soil biomass. Bacteria, actinomycetes, and protozoa can tolerate more soil disturbance than fungal populations so they dominate in tilled soils while fungal and nematode populations tend to dominate in untilled (Silva et. al. 2013). A long-term study carried out across different regions of Nepal by NARC's SSD shows a greater number of fungal populations in the Terai region followed by the High Hill region (SSD 2019). Similarly, a greater number of bacterial populations were found in the Terai region followed by the High Hill and Mid-Hill regions. A greater number of the Azotobacter population was found in the Mid Hill regions. However, there was no distinct trend of the microbial population across fertilizer treatments.

Soil aeration and microorganism population

Microorganism populations in soil could be controlled by soil porosity, as greater amounts of pore space meaning higher counts of microbes (Collins 2010). Well-tilled soil is well aerated and favors microorganism growth. The microbial population is found to be more in aerobic (O_2-rich) soil compared to anaerobic (CO_2–rich) soil (McNabb and Startsev 2009). A major contributor to poor aeration is soil compaction. A count of Azotobacter, Azospirillum, Rhizobium, cyanobacteria, and phosphorus- and potassium-solubilizing microorganisms and mycorrhizae is found to be higher under long-term no-till or minimum-tillage soil (Bhardwaj et al. 2014).

Organic matter and aeration have a positive correlation in building the microorganism population where depth has a negative correlation. Further, soil aeration and organic matter decreases with increasing soil depth, thus decreasing the microorganism population. This indicates that surface soil is rich in microorganisms. In the present context, the soil is being compacted with heavy agricultural equipment, which has created a soil horizon devoid of air space. The soil density has increased resulting in the decrease in the porosity of the soil and limiting microorganism growth. Similar is the case with organic matter, where present agricultural practice uses chemical fertilizer, limiting the use of organic matter. Consequently, microorganisms are deprived of food and their growth has been checked. This has created an imbalance in the soil ecosystem that has resulted in poor structure and less fertile soil.

Effect on greenhouse gas (GHG) emissions from soil

After carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) are two important greenhouse gases that are emitted from agriculture practices. Agricultural intensification contributes directly to emissions through a variety of processes. Most of the N_2O from soils is produced mainly by two biological processes, namely, nitrification and denitrification. There are very few studies in Nepal observing the effects on GHG emissions from soil/land use change, though Awasthi (2004) found that land-use changes in the Mid-Hills from the forest or grassland to flooded rice fields were significant sources for CH_4 emission into the atmosphere.

Effect of agrochemicals on soil microbial activities

Several herbicides can alter the symbiotic association between legume plants and rhizobacteria and hinder the vital processes of N-fixation (Singh and Wright 2000; Meena et al. 2015). Some of the examples are paraquat, glyphosate, pendimethalin, which reduce N-fixation in legumes (Dos Santos et al. 2005; Strandberg et al. 2004).

Similarly, fungicides, especially copper (Cu)-based fungicides, have a deleterious effect on the population of N-fixing bacteria (Van Zwieten et al. 2003). Both mancozeb and chlorothalonil can decrease the process of nitrification and denitrification (Kinney et al. 2005). Similarly, insecticides have a negative effect on soil microbes. The growth and population of Azotobacter are significantly inhibited by phosphamidon, malathion, fenthion, methyl phosphorothioate, and parathion (Panday and Singh 2004).

Therefore, to create healthy and fertile soil, we must provide an environment that favors the growth of microorganisms. For this addition of organic matter, loosening the soil mass, providing the optimum moisture in soil, reducing heavy agricultural equipment, and replacing chemicals with alternative sources of manure are steps toward creating eco-friendly soil with high microbial populations.

Microbial Uses in Nepalese Agriculture

Microbes are used for various purposes, including making biofertilizers, biopesticides, west decomposers, food and beverage manufacture, and fermentation of industrial products. Special reference is made here for managing nutrients as a fertilizer, growth-promoting substance, or as a decomposer and symbiotic nutrient supplier.

In Nepal, the exploitation of microbes as biofertilizers is carried out through research and production activities such as isolation, identification, and characterization of Rhizobium and Azotobacter, and symbiotic and asymbiotic N fixers by NARC's SSD in the government sector. In addition, some private laboratories have also initiated the production of biofertilizers and biopesticides.

Microbes used as Biofertilizers in Nepal

Biofertilizers are substances produced through biological processes with a significant nutrient value that can be used as effective sources of nutrients. These contain living microorganisms that, when applied to soil, seed, or plant surfaces, colonize the rhizosphere or the interior of the plant and promote growth by increasing the availability of nutrients to the host plant. Unlike manures and fertilizers, biofertilizers add nutrients to the system through the natural process of atmospheric fixation (e.g., of N) or by making nutrients available through the process of mobilization and solubilization (e.g., for phosphorus, P). Some of these species also stimulate plant growth through the synthesis of growth-promoting substances. The microorganisms in biofertilizers also restore the natural nutrient cycle and build SOM that supports healthy plant growth and soil health, which are fundamental for sustainable soil fertility. Therefore, biofertilizers can contribute significantly toward reducing the use of chemical fertilizers and can play a significant role in Nepal for enriching soil fertility and fulfilling plant nutrient requirements in a sustainable way. Biofertilizers such as Rhizobium, Azotobacter, Azospirillum, and blue-green algae (BGA) have been in use for a long time in Nepal. Based on their mode of nutrient synthesis or release in soil or plants, biofertilizers can be categorized into several groups, which are as follows:

Rhizobium species

Rhizobium sp., the symbiotic N-fixing bacteria, is an important group among the micro-organisms used as biofertilizers. Rhizobia fix atmospheric N (40–250 kg N ha^{-1} yr^{-1}) symbiotically into the root's nodules of host legume plants. Rhizobia can also be utilized through the growing of leguminous plants as a green manure that adds N through fixation as well as through the decomposition of N-rich legume biomass in soil. During the fiscal year 2018/19, NARC's SSD produced 4507 packets of biofertilizers for different crops including lentil, soybean, cowpea, pea, black gram, and some grasses, and 3510 packets were distributed to farmers and Agricultural Agencies for practical use in their fields (SSD 2018/19).

Both inoculation successes and failures at the field level have been reported in the literature. Responses to Rhizobium inoculation have mostly been demonstrated with grain legume crops, particularly lentil, chickpea, soybean, groundnut, black gram, and faba bean. Inoculation of Rhizobium increased the grain yield of different legumes from 17 to 60% and are known to leave behind some residual nitrogen in the soil (Maskey et al. 2001). In some experiments, a significant residual effect was reported in the yield of subsequent crops such as wheat, rice, and maize. The maximum residual effect was seen in soybean, which increased the yield of subsequent crops of wheat by 65.9% over un-inoculated crops (SSD 2015).

Azolla

Azolla is a free-floating water fern that fixes atmospheric N in association with BGA (Anabaena azollae). Anabaena in association with Azolla contributes up to 60 kg N ha^{-1} season^{-1} and also enriches soils with OM (Stewart et al. 2005). Azolla as a biofertilizer is commonly used in rice farming systems. Azolla is most found naturally in stagnant water and is also used as a biofertilizer in rice in Nepal. There remains the need for wider application of Azolla because farmers in Nepal still lack knowledge about its use.

In Nepal, A. Pinnate and A. filiculoides are commonly found in natural water and swampy lands. Azolla requires phosphorus (15–20 kg ha^{-1}) and in very deficient soil deficiency symptoms such as purple color occur (Maskey and Bhattarai 1984). Molybdenum is beneficial for the adequate growth of Azolla (Adhikary and Bhattrai 2000). Azolla alone can increase rice yield by at least 12–14% without any additional N fertilizer, though recommended doses of P and K fertilizers are needed to meet the nutrient requirement of the crop (Adhikary et al. 2015).

Blue Green Algae (BGA)

Blue-Green Algae (BGA) are also known as Cynobacteria. They are either single-celled or filamentous multicellular. The N-fixing BGA possesses a special structure called Heterocyst. The standing water of the rice field encourages the growth of Blue-Green Algae (BGA), and these BGA possess photosynthesis abilities as well as biological nitrogen fixation abilities. BGA belonging to the general genus Nostoc, Anabaena, Tolypothrix, or Aulosira fix atmospheric N and are used as inoculants for upland and lowland paddy rice.

Blue-green algae are the dominant N-fixer. In addition to N-fixing, they excrete vitamin B12, auxin, and ascorbic acid, which contribute to rice growth. They fix atmospheric N equivalent to 20–30 kg h^{-1} yr^{-1}. Azollae and BGA (Anabaena azollae) are actively involved in the symbiotic association and fix atmospheric N, after which the host plant (Azolla) provides a carbon source while Anabana azollae fix atmospheric N and transfer it to the azolla, which then multiplies rapidly. In Nepal very limited research, demonstration, and promotion activities are carried out regarding BGA.

Free-living N-fixing bacteria

Free-living N-fixing bacteria such as *Azotobacter, Azospirillum*, and *Clostridium* sp. also fix N in nonlegume crops such as rice, wheat, barley, millet, and cotton. These are not as common as Rhizobia, but they have a potential for N-fixing in non-legume crops. Azotobacter have been used in cereals (e.g., wheat and barley), potatoes, and vegetables, while Azospirillum inoculations are recommended mainly for use in sorghum, millets, maize, sugarcane, and wheat. The population of Azotobacter in Nepalese soils is very low, that is, not more than 10,000–100,000 g^{-1} soil. The population of Azotobacter is mostly influenced by other microorganisms present in the soil; for instance, Cephallosporium is mostly found in soil that restricts the growth of Azotobacter. Several field experiments have been conducted in Nepal on the Azotobacter inoculation of seeds and seedlings in rice, wheat, maize, tomato, potato, cabbage, and other crops under different agroclimatic conditions. The lack of organic matter in soil is a limiting factor for its multiplication, though the effect of Azotobacter was increased by 154% when compost was used. Maskey and Bhattrai (1984) reported yield increases of 6–12% in rice and 8–12% in wheat after inoculating Azotobacter. Baral and Adhikary (2013) reported that inoculation of only Azotobacter increased grain yield in maize 15–35% and that the benefit is higher in the absence of chemical fertilizer application. Inoculation of Azotobacter also increased yield 5% in tomatoes and 3.5–55% in cauliflower (SSD2000).

In Nepal, Azotobacter is mainly isolated, cultured, produced, and supplied by the Soil Science Division of NARC. Besides the Soil Science Division, private agro supply companies import biofertilizers with different trade names, though their quality is not assured.

Phosphate-solubilizing bacteria (PSB)

Phosphate-solubilizing bacteria (PSB), such as *Pantoea agglomerans* or *Pseudomonas putida* can solubilize the insoluble phosphate from organic and inorganic phosphate sources. Due to the immobilization of phosphate by mineral ions such as Fe^{2+}, Fe^{3+}, Al^{3+}, and Ca^{2+} or organic acids, the available phosphate (H_2PO_4) in soil absorbed by plants can be as low as 20% of added P fertilizer. In Nepal, very limited research work has been carried out on PSB, though PSB as a bio-fertilizer in various trade names is now available through importation from other countries.

Vesicular Arbuscular mycorrhizal (VAM)

A mutually beneficial (symbiotic) association between numerous fungi and the roots of higher plants is called mycorrhiza. The available technique of inoculation is to collect infested roots and use them for subsequent infection, a method that limits widespread application. These inoculations are to prepare per-inoculated transplants for coffee, tea, cocoa, papaya, and oil palm.

Mycorrhizas increase the longevity of feeder roots and root surface area by forming a mantle and spreading mycelia into the soil, which in turn enhances the rate of absorption of macro- and micronutrients and water. Mycorrhizas also play a key role in the selective absorption of immobile (P, Zn, and Cu) and mobile (S, Ca, K, Fe, Mn, Cl, and N) elements to plants (Tinker 1984). Vesicular Arbuscular mycorrhizal (VAM) fungus reduces the plant response to soil stresses caused by high salt, drought, and toxicity associated with heavy metals, mine spoils, and minor element (e.g., Mn) deficiencies. Among the different types of endomycorrhizae Glomus and Acaulosporus are predominantly found in upland soil (Bajracharya et al. 2004b). The organic amendment significantly increases the biomass of VAM and enhances the rehabilitation of eroded soil (Vaidya et al. 2007).

Limitations of Biofertilizer Adoption in Nepal

Although the use of biofertilizers has more benefits compared to the use of inorganic fertilizers, there are certain limitations to its widescale adoption in Nepal. Some of these limitations include (i) unavailability of appropriate inoculum, (ii) preservation and transport of inoculum, (iii) poor farmers' awareness of the use of biofertilizers, (iv) high cost of production, (v) lack of commercial operation, and (vi) slow effects on crops. These issues should be addressed to utilize the potential of biofertilizers for developing commercial products available to Nepalese farmers.

8.5 Summary and Conclusion

To keep our soil healthy, all of the physical, chemical, and biological properties have to be properly managed. Nepalese soils are developed from micaceous parent materials such as phyllites, schists, gneisses, granites, and others, and therefore most of the soil contains higher proportions of mica. Loam and sandy loam are the most dominant soil textures in both hills and alluvial terraces. However, this varies with agroecology and land use types. The sub-angular blocky structure is most common in Nepal. In Terai, angular blocky is a common structure in clayey-type soils. Because the use of organic inputs is common in Nepalese agriculture, particularly in the Hills and Mid-Hills, most of the soils in the hills and mountainous are friable. However, hard consistency predominates in areas where organic manure is limited, particularly in the Terai region.

Nepalese farmers in the hills and river valleys apply a sufficient amount of organic inputs, including farmyard manure and compost, to their field crops. Soils are more acidic at higher altitudes (hills and mountains) and in the eastern Terai compared to the western part of the country. The total N content in Nepalese soil lies mostly in the medium range, while available phosphorus and potassium content are in the higher range. Among the micronutrients, B, Zn, and Mo are deficient in the soil (though in patches), while (Cu), iron (Fe), and manganese (Mn) are at adequate levels.

The soils of Nepal are heterogeneous, therefore requiring multiple technologies for their sustainable management. Most farmers manage soils using indigenous practices that are organic based in the Hill and Mountain regions, where chemical fertilizers are used as a supplement. Farmers in the Terai region use more chemical fertilizers compared to farmers in the Hill and Mountain regions, and organic inputs are used as a supplement. Soil erosion and acidification are the most pertinent soil problems in Nepal. Careful management of soil with adequate and sustainable management practices is the need of the day to improve soil fertility in Nepal.

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