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Edited by

Ranjan Bhattacharyya

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Soil Health Insights from India

Douglas L. Karlen, Soil Health Series Editor

Soil Health and Sustainable Agriculture in India is the fourth volume in the Soil Health Series being published by the Soil Science Society of America (SSSA) and Wiley. Volumes one and two provide the background and general methods for assessing soil biological, chemical, and physical properties and processes. Building upon that soil health foundation, a series of volumes are being added to show how the concept is being applied to protect and improve soil resources around the globe. Volume four is edited by Dr. Ranjan Bhattacharyya, an excellent scientist from the Division of Environment Science, ICAR-Indian Agricultural Research Institute. The size and regional agroecological diversity of India make this volume an important contribution to the Series.

The subcontinent of India has heterogeneous landforms and a variety of climatic conditions that create subtle but very important differences in critical soil health indicators and management practices needed to sustain the soil resources. Lofty mountains, river deltas, high altitude forests, and peninsular plateaus have a variety of geological formations, endowed with temperature regimes ranging from arctic cold to equatorial heat, and rainfall extremes from aridity (<10 cm) to sites receiving the world's maximum average annual rainfall (1120 cm).

Soil health and sustainable agricultural practices in this wide variety of agroecological regions are discussed by highly respected authors in fifteen chapters. Beginning with a broad overview of India's agricultural ecoregions and soil health challenges, specific soil health properties, processes, and indicators are discussed for Himalayan, Arid, Semi-Arid, Sub-Humid, Coastal, and Southern Peninsular Ecoregions. Indian Vertisols are also examined in depth. Soil management strategies to maintain or improve soil health are then examined for those ecoregions, saline, acidic, and waterlogged soils. Finally, conservation agriculture strategies for enhancing soil health and mitigating greenhouse gas (GHG) emissions and crop residue management strategies for dryland and irrigated areas are explored. A series of recommendations for long-term soil health enhancement throughout the subcontinent are presented in Chapter 15. The editor, authors, and I hope you find this volume useful in helping guide sustainable agricultural management practices that enhance productivity while protecting the fragile soil, water, and air resources within India or wherever you may be located in the world.

Preface

Land degradation in India is a pervasive problem and a major soil health challenge. Despite years of study and substantial investment in remediation and prevention, soil erosion continues to be a major environmental problem. Changing climate and weather patterns are further exacerbating the situation. India's soil degradation affects approximately 120 million hectares of land. Issues include water erosion, soil acidification, flooding or waterlogged soils, wind erosion, salinity, and other combined factors. This is extremely serious, as India supports 18% of the world's population. Major causes of soil degradation are both natural and human induced. Natural causes mainly include droughts, floods, and tornadoes. Soil degradation caused by human activities arises due to deforestation, suboptimal agricultural practices, inadequate forest management, surface mining, urban expansion, and accelerated development. Poor farming practices involve excessive tillage, unbalanced use of inorganic fertilizers, improper irrigation techniques, insufficient organic inputs, and poor crop cycle planning.

Managing agricultural land to achieve soil health can help optimize agricultural inputs to soil (including fertilizer, water, energy, etc.) thereby reducing costs while maintaining or improving yields. Improving soil health improves adaptation to the effects of climate change, and will also contribute to carbon neutrality objectives.

This book examines the challenges and opportunities related to restoring and enhancing soil health in degraded farmland in India. It includes information on various soil restoration practices such as tree-based ecological restoration, conservation agriculture, integrated nutrient management, soil management in dryland agriculture, grassland management, and organic farming systems. The book discusses the importance of new fertilizer formulations for better input efficiency, as well as quick soil assessment and monitoring. You will find recommendations for sustainable soil management to support India's growing population. These include ensuring food safety, protecting biodiversity, adapting to climate change, managing waste, addressing soil pollution, and comprehensive soil management.

Ranjan Bhattacharyya

1

Agricultural Ecoregions and Soil Health Challenges Within the Indian Sub-Continent

Shrila Das, Dibyendu Mukhopadhyay, and Ranjan Bhattacharyya

Chapter Overview

Every agro-ecological zone in India faces various soil health challenges, including deforestation, overgrazing, changes in land use (such as converting forests to farms), cultivation of steep slopes, and degradation of marginal lands due to human activity. Agriculture-specific activities, such as overexploitation of vegetation, removal of crop residues or in situ burning, and minimal or no addition of organic manures coupled with intensive cultivation, are leading to the depletion of soil organic carbon (SOC) and degradation of soil quality. Major challenges to the conservation of soil resources and the maintenance of soil health include water and wind erosion, salinity, decline in SOC, nutrient imbalance, and soil pollution and contamination. This chapter aims to discuss these soil health challenges encountered in different agro-ecological zones.

Introduction

India is known for its diverse landforms, ranging from lofty mountains and riverine deltas to high-altitude forests and peninsular plateaus, and the variety of climatic conditions associated with them. The range of geological formations are accompanied by temperatures varying from arctic cold to equatorial heat and rainfall varying from extreme aridity (less than 10 cm annually) to the world's highest rainfall (1,120 cm per annum). To develop long-term land use strategies, India has been divided into 20 agro-ecological regions (AERs) with 60 agro-ecological subregions (AESRs) based on diverse soil, bioclimatic, and physiographic conditions. AER s of India with their dominant soil characteristics are described in Table 1.1.

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Edited by Ranjan Bhattacharyya.

Table 1.1 Agro-ecological Regions of India with their Dominant Soil Characteristics.

	AER	% of total geographic area	Soil characteristics	Moisture and temperature regimes
1	**Western Himalayas, cold arid ecoregion**	4.7	Desert and calcareous soils (Cryorthents and Cryorthids)	Aridic soil moisture and cryic soil temperature regimes
2	**Western Plain, Kachchh and part of Kathiawar Peninsula, hot arid ecoregion**	9.78	Desert and saline soils (Torripsamments, Camborthids, Calciorthids, Salorthids, and Natrargids)	Aridic soil moisture and hyperthermic soil temperature regimes
3	**Deccan plateau, hot arid ecoregion**	1.5	Red and black soils (Rhodustalfs, Haplustalfs, Ustropepts, and Pellusterts)	Aridic-ustic soil moisture and isohyperthermic soil temperature regimes
4	**Northern Plain (and Central Highlands) including Aravallis, hot semi-arid ecoregion**	9.8	Alluvium-derived soils (Ustochrepts, Natrustalfs, Ustipsamments, and Ustifluvents)	Typic-ustic soil moisture with hyperthermic soil temperature regime
5	**Central (Malwa) Highlands, Gujarat plains, and Kathiawar Peninsula ecoregion**	5.4	Medium and deep black soils (Ustochrepts and Chromusterts)	Typic-ustic soil moisture with hyperthermic and isohyperthermic soil temperature regime.
6	**Deccan Plateau, hot semi-arid ecoregion**	9.5	Shallow and medium black soils (Ustorthents, Ustropepts, and Chromusterts/Pellusterts)	Ustic soil moisture with (iso) hyperthermic soil temperature regime
7	**Deccan Plateau (Telangana) and Eastern Ghats, hot semi-arid ecoregion**	9.5	Shallow and medium black soils (Ustorthents, Ustropepts, and Chromusterts/Pellusterts)	ustic soil moisture with (iso) hyperthermic soil temperature regime

8	**Eastern Ghats and Tamil Nadu Uplands and Deccan (Karnataka) Plateau, hot semi-arid ecoregion**	5.2	Red and black soils (Ustorthents, Rhodustalfs, Ustropepts, and Chromusters)	Moisture soil regime is ustic and temperature regime is the isohyperthermic
9	**Northern Plain, hot subhumid (dry) ecoregion**	3.7	Alluvium-derived soils (Ustochrepts, Haplustalfs, Eutrochrepts, and Ustifluvents)	Ustic soil moisture with hyperthermic soil temperature regime
10	**Central Highlands (Malwa and Bundelkhand), hot subhumid (dry) ecoregion**	5.8	Red and black soils (Ustorthents, Ustochrepts, Haplustalfs, and Chromusterts)	Ustic soil moisture with hyperthermic soil temperature regime
11	**Chattisgarh/Mahanadi Basin agro-ecoregion**	4.3	Red and yellow soils (Ustorthents, Ustochrepts, Haplustalfs, Rhodulstalfs, and Plinthustalfs)	Ustic soil moisture with hyperthermic soil temperature regime
12	**Eastern Plateau (Chhotanagpur) and Eastern Ghats, hot subhumid ecoregion**	8.2	Red and lateritic soils (Ustochrepts, Haplustalfs, Plinthustalfs, Paleustalfs, Haplustults, and Rhodustalfs)	Ustic soil moisture with hyperthermic soil temperature regime
13	**Eastern Plain, hot subhumid (moist) ecoregion**	3.4	Alluvium-derived soils (Ustifluvents, Ustochrepts, Eutrochrepts, Aquic Hapludalfs, and Haplustalfs)	Udic and ustic soil moisture regime
14	**Western Himalayas, warm subhumid (to humid with inclusion of perhumid) ecoregion**	6.3	Brown forest and podzolic soils (Eutrochrepts, Hapludalfs, Haplustalfs, Hapludolls, Haplohumults, and Haplaquepts)	Mesic, thermic, and cryic-mesic soil temperature regime
15	**Assam and Bengal Plain, hot subhumid to humid (inclusion of perhumid) ecoregion**	3.7	Alluvium-derived soils (Haplaquepts, Haplaqualfs, Dystrochrepts, Eutrochrepts, Fluvaquents, Hapludalfs)	Udic-ustic (to Udic) and Hyperthermic

(*Continued*)

Table 1.1 (Continued)

	AER	% of total geographic area	Soil characteristics	Moisture and temperature regimes
16	**Eastern Himalayas, warm perhumid ecoregion**	2.9	Brown and red hill soils (Haplumbrepts, Paleudults, Hapludolls, and Argiudolls)	Udic soil moisture regime and mesic, thermic, and hyperthermic soil temperature regime
17	**Northeastern Hills (Purvachal), warm perhumid ecoregion**	3.3	Red and lateritic soils (Hapludults, Paleudults, Dystrochrepts, Hapludalfs, and Rhodustalfs)	Udic soil moisture with hyperthermic, thermic soil temperature regime
18	**Eastern Coastal Plain, hot subhumid to semiarid ecoregion**	2.6	Coastal alluvium-derived soils (Haplaquents, Halaquepts, Ustifluvents, Pellusterts, and Ustropepts)	Udic and ustic soil moisture regime and mesic, thermic soil temperature regime
19	**Western Ghats and Coastal Plain, hot humid-perhumid ecoregion**	3.6	Red, lateritic, and alluvium-derived soils (Dystropepts, Eutropepts, Hapludults, and Haplaquepts with localized Haplorthorx)	Udic and ustic soil moisture regime and isohyperthermic temperature regime
20	**Islands of Andaman-Nicobar and Lakshadweep, hot humid to perhumid island ecoregion**	0.3	Red loamy soils including marine alluviumderived soils along the coast. They qualify for the Great Groups of Hapludalfs, Dystropepts, Eutropepts and Sulfaquents (along the coast).	Udic soil moisture and isohyperthermic soil temperature regime

1) **Western Himalayas, cold arid ecoregion**
   - Covers 4.7% of the total geographical area (TGA) of the country
   - Desert and calcareous soils (Cryorthents and Cryorthids)
   - Represents aridic soil moisture and cryic soil temperature regimes
2) **Western Plain, Kachchh and part of Kathiawar Peninsula, hot arid ecoregion**
   - Covers 9.78% of the TGA of the country
   - Desert and saline soils (Torripsamments, Camborthids, Calciorthids, Salorthids, and Natrargids)
   - Represents aridic soil moisture and hyperthermic soil temperature regimes
3) **Deccan plateau, hot arid ecoregion**
   - Covers 1.5% of the TGA of India
   - Red and black soils (Rhodustalfs, Haplustalfs, Ustropepts, and Pellusterts)
   - Represents the aridic-ustic soil moisture and isohyperthermic soil temperature regimes
4) **Northern Plain (and Central Highlands) including Aravallis, hot semi-arid ecoregion**
   - Covers 9.8% of the TGA of the country
   - Alluvium-derived soils (Ustochrepts, Natrustalfs, Ustipsamments, and Ustifluvents)
   - Represents typic-ustic soil moisture with hyperthermic soil temperature regime
5) **Central (Malwa) Highlands, Gujarat plains, and Kathiawar Peninsula ecoregion**
   - Covers 5.4% of the TGA of the country
   - Medium and deep black soils (Ustochrepts and Chromusterts)
   - Represents typic-ustic soil moisture with hyperthermic and isohyperthermic soil temperature regime.
6) **Deccan Plateau, hot semi-arid ecoregion**
   - Covers 9.5% of the TGA of the country
   - Shallow and medium black soils (Ustorthents, Ustropepts, and Chromusterts/Pellusterts)
   - Represents ustic soil moisture with (iso) hyperthermic soil temperature regime
7) **Deccan Plateau (Telangana) and Eastern Ghats, hot semi-arid ecoregion**
   - Covers 9.5% of the TGA of the country
   - Shallow and medium black soils (Ustorthents, Ustropepts, and Chromusterts/Pellusterts)
   - Represents ustic soil moisture with (iso) hyperthermic soil temperature regime

8) **Eastern Ghats and Tamil Nadu Uplands and Deccan (Karnataka) Plateau, hot semi-arid ecoregion**
   - Covers 5.2% of the TGA of the country
   - Red and black soils (Ustorthents, Rhodustalfs, Ustropepts, and Chromusters)
9) **Northern Plain, hot subhumid (dry) ecoregion**
   - Covers 3.7% of the TGA of the country
   - Alluvium-derived soils (Ustochrepts, Haplustalfs, Eutrochrepts, and Ustifluvents)
   - Represents ustic soil moisture with hyperthermic soil temperature regime
10) **Central Highlands (Malwa and Bundelkhand), hot subhumid (dry) ecoregion**
   - Covers 5.8% of the TGA of the country
   - Red and black soils (Ustorthents, Ustochrepts, Haplustalfs, and Chromusterts)
   - Represents ustic soil moisture with hyperthermic soil temperature regime
11) **Chattisgarh/Mahanadi Basin agro-ecoregion**
   - Covers 4.3% of the TGA of the country
   - Red and yellow soils (Ustorthents, Ustochrepts, Haplustalfs, Rhodulstalfs, and Plinthustalfs)
12) **Eastern Plateau (Chhotanagpur) and Eastern Ghats, hot subhumid ecoregion**
   - Covers 8.2% of the TGA of the country
   - Red and lateritic soils (Ustochrepts, Haplustalfs, Plinthustalfs, Paleustalfs, Haplustults, and Rhodustalfs)
   - Represents ustic soil moisture with hyperthermic soil temperature regime
13) **Eastern Plain, hot subhumid (moist) ecoregion**
   - Covers 3.4% of the TGA of the country
   - Alluvium-derived soils (Ustifluvents, Ustochrepts, Eutrochrepts, Aquic Hapludalfs, and Haplustalfs)
   - Represents udic and ustic soil moisture regime
14) **Western Himalayas, warm subhumid (to humid with inclusion of perhumid) ecoregion**
   - Covers 6.3% of the TGA of the country
   - Brown forest and podzolic soils (Eutrochrepts, Hapludalfs, Haplustalfs, Hapludolls, Haplohumults, and Haplaquepts)
   - Represents mesic, thermic, and cryic-mesic soil temperature regime
15) **Assam and Bengal Plain, hot subhumid to humid (inclusion of perhumid) ecoregion**
   - Covers 3.7% of the TGA of the country
   - Alluvium-derived soils (Haplaquepts, Haplaqualfs, Dystrochrepts, Eutrochrepts, Fluvaquents, Hapludalfs)

16) **Eastern Himalayas, warm perhumid ecoregion**
   - Covers 2.9% of the TGA of the country
   - Brown and red hill soils (Haplumbrepts, Paleudults, Hapludolls, and Argiudolls)
   - Represents udic soil moisture regime
17) **Northeastern Hills (Purvachal), warm perhumid ecoregion**
   - Covers 3.3% of the TGA of the country
   - Red and lateritic soils (Hapludults, Paleudults, Dystrochrepts, Hapludalfs, and Rhodustalfs)
   - Represents udic soil moisture with hyperthermic, thermic soil temperature regime
18) **Eastern Coastal Plain, hot subhumid to semiarid ecoregion**
   - Covers 2.6% of the TGA of the country
   - Coastal alluvium-derived soils (Haplaquents, Halaquepts, Ustifluvents, Pellusterts, and Ustropepts)
19) **Western Ghats and Coastal Plain, hot humid-perhumid ecoregion**
   - Covers 3.6% of the TGA of the country
   - Red, lateritic, and alluvium-derived soils (Dystropepts, Eutropepts, Hapludults, and Haplaquepts with localized Haplorthorx)
20) **Islands of Andaman-Nicobar and Lakshadweep, hot humid to perhumid island ecoregion**
   - Covers 0.3% of the TGA of the country.
   - Medium to very deep, Red loamy soils including marine alluvium derived soils along the coast, hot perhumid (Andaman and Nicobar Islands) to highly calcareous and sandy in nature, hot humid (Lakshadweep Group of Islands).

Soil Health Challenges in India

Deforestation and Removal of Natural Vegetation, Overgrazing, Change in Land Use Plan

Soil degradation in India affects an estimated 120 million hectares (Mha) of land, encompassing issues such as water erosion, acidification, flooding, wind erosion, salinity, and various other factors. This situation is particularly critical given that India is home to 18% of the global human population and 15% of the world's livestock population, yet it only possesses 2.4% of the world's land area (Bhattacharyya et al., 2015). Deforestation, removal of natural vegetation, overgrazing, and changes in land-use plans are some of the human-induced forms of soil degradation. The UN Food and Agricultural Organization (FAO) defines deforestation as the conversion of forested land to another land use or a long-term reduction in tree canopy cover to below 10%.

A new study by Utility Bidder, a UK-based comparison site for energy and utility costs, ranks the countries contributing the most to global deforestation rates in 2023. India ranks second, having destroyed an average of 668,400 ha of forestry between 2015 and 2020. Deforestation and overgrazing have led to land degradation in eight Indian states, where over 20% of land area is now wasteland (NRSA, 2019). Vegetation loss is driven by excessive cutting beyond the silvicultural permissible limit, unsustainable fuelwood and fodder extraction, agricultural encroachment into forest lands, forest fires, and overgrazing, all of which contribute to land degradation. Additionally, the clearing of forest areas due to shifting cultivation results in the loss of primary vegetation and the formation of secondary vegetation (Ray et al., 2021). Moreover, owing to shortening of shifting cultivation cycles, the secondary vegetation does not have adequate time to regenerate. The repeated short-cycle use of land eventually converts the area under degraded fallow. Therefore, shifting cultivation is considered the single most important factor causing forest degradation in the northeastern Himalayan region. After a short jhum cycle (shifting cultivation), weedy species such as *Eupatorium odoratum*, *Imperata cylindrica*, *Mikania micrantha*, and *Saccharum spontaneum* colonize the affected areas (Saxena & Ramakrishnan, 1983). A cattle population of 467 million grazes on 11 Mha of pastures, averaging 42 head per hectare, which far exceeds the sustainable threshold of five animals per hectare (Sahay, 2015). This high livestock density in arid regions leads to overgrazing, which decreases infiltration and accelerates runoff and soil erosion. As a result, soil loss due to overgrazing is 5–41 times greater than normal at the mesoscale and 3–18 times greater at the macroscale (Sharma, 1997).

Change in a land use system is a process, by which human activities transform the natural landscape or existing land use to another land use in which the functional roles of land for economic activities are emphasized. A report of meta-analysis (more than 1,786 paired datasets) on land uses from Indian (1990–2019) indicated that the maximum loss of SOC was under grasslands at 36.1%, followed by forest lands, plantation lands (35.5%), cultivated lands (31.1%), barren lands (27.3%), and horticulture lands (11.5%; Padbhushan et al., 2022). Land use changes from anthropogenic activities also modify the land surface temperature and surface energy and finally cause changes within microclimates at the regional level and at local level. Kaliraj et al. (2017) reported that about 18% of the fallow lands and barren lands were converted into settlements and about 5.15% and 5.86% of the land uses were converted into barren and fallow lands, respectively, in coastal plains of southern Tamil Nadu, India, between 2000 and 2010. Therefore, any change in land use systems (cultivation or fallow land) will have an impact on soil health and its resilience. The transformation of tea garden/forest land area into the field crop production and vice versa definitely have an effect on the soil biota and the surrounding ecosystem. The changes in mineralizable carbon (Figure 1.1)

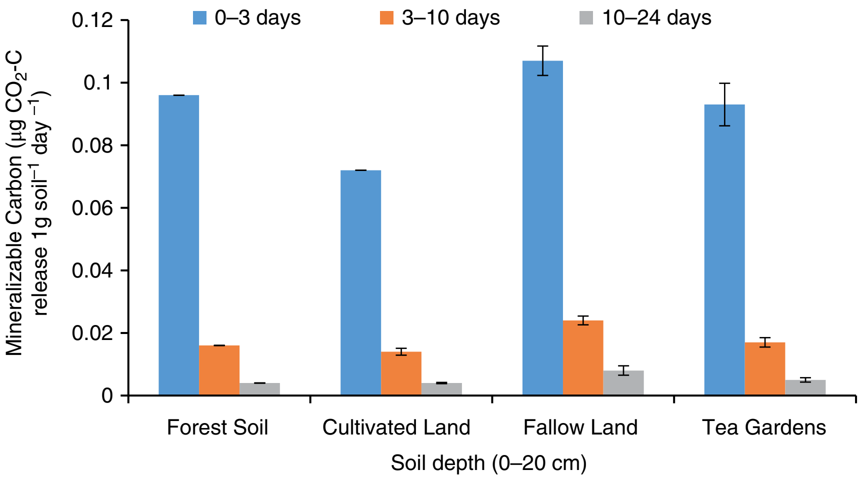

Figure 1.1 Mineralizable carbon (µg of CO_2-C released per gram of soil per day) fractions in soils under different land use systems. Error bars indicate the standard deviation ($P = 0.05$).

in soil under different land use patterns show the need for effective technological intervention to build up carbon sequestration in soil as well as to improve the microbial biomass carbon (Pal et al., 2020). Dharumarajan et al. (2017) found that erratic rainfall distribution, poor soil fertility, and ground water deterioration are the factors responsible for the area of fallow lands in Tamil Nadu expanding with increasing costs of cultivation. Moreover, there is increase in population growth (from 11.42% in 1991 to 14.20% in 2014) in the Indian coastal tracts, with rapid transformation of built-ups, settlements, and recreational uses directly causing degradation of the coasts (Kaliraj et al., 2017).

The changes in mineralizable carbon at different incubation periods (0–3, 3–10, and 10–24 days) at (0–20) cm soil depth are shown in Figure 1.1. Significant differences were observed in some of the ecosystems (tea gardens, fallow land) with the given period of incubation, while the changes were not significant in most of the cases at the initial period of incubation (Pal et al., 2020).

Cultivating Steep Slopes and Degrading Marginal Lands

According to land capability classification, steep land (with shallow depth, coarse texture with >30% slope) is classed as unsuitable for farming as it may cause water erosion. In addition, low moisture availability in arid climates aggravates drought. Cultivation on steep slopes leads to severe soil health challenges such as soil erosion up to 100 ton ha^{-1}, which can remove top soil in 20 years (based on the universal soil loss equation; Verma et al., 2018); rapid drying of the upper part of soil facing the sun, leading to sparse or nil vegetative cover during dry season; soil fertility impoverishment because of leaching loss of nutrients, which leads to soil acidity, particularly in permeable soils (Entisols, Inceptisols, Oxisols); and drought, owing to wind erosion being more intense on steep land. Marginal lands are defined as being severely limited by various soil physical, chemical, and biological properties (texture, drainage, fertility, slope or climate; Esch et al., 2018). Marginal lands are found in different part of India. Soil attributes that are indicators of marginal land (salt content, electrical conductivity, drainage, base saturation, salinity, sodicity, rooting depth, organic carbon, cation exchange capacity, etc.) should be addressed; otherwise, soil quality, as well as sustainability of the land, will be hampered (Csikós & Tóth, 2023). Important indicators corresponding to soil processes are given in Table 1.2.

Table 1.2 Soil Health Indicators Affecting the Soil Processes.

Soil health indicators	Soil processes
Physical	
Soil texture	All the physico-chemical processes
Aggregate stability of soil	Rate of infiltration, aeration, root density
Water holding capacity of soil	Characteristics of soil moisture retention
Surface and subsurface hardness	Seed germination, root growth, internal drainage
Chemical	
pH	Nutrient availability, toxicity
Available N, P, K	Availability of N-P-K from soil to plants
Other minor elements	Micronutrients, nutrient transformation
Biological	
Stock of organic matter in soil	Carbon storage, water and nutrient reserves
Carbon fractions	Supporting biological activities
Mineralizable nitrogen	Ability to supply nitrogen
Residue decomposition	Microbial population, nutrient mobilization to plants

Threats to Conservation of Soil Resources

Erosion by Water, Wind, and Cyclonic Storms

Climate change, particularly the changing trends in precipitation, have a severe impact on soil erosion, especially in hilly regions. The effect of increased precipitation and/or increased intensity may vary between different slope categories. For moderate slopes, there will be proportionately higher increase of soil erosion mainly because of increased erosive power and the availability of erodible material. On very steep slopes, the proportional increase in erosion may be less because of limiting erodible materials, such as hard rock outcrops. Another aspect of climate change is conversion of snowfall to rainfall. The frequency of extreme rain events (>100 mm intensity) has increased over central India from 1951 to 2015 (Goswami et al., 2006). Such extreme precipitation results in severe soil erosion, which affects the productive capacity of the soils (Mandal et al., 2010). The critical permissible limit of soil erosion is considered as $1000\,t\,km^{-2}\,yr^{-1}$. The soil loss map (Figure 1.2) shows that in the northeastern states (Nagaland, Meghalaya, Arunachal Pradesh, Assam, Chhattisgarh, and Jharkhand), erosion rates are above the critical permissible limits. Other states such as Uttar Pradesh, Uttarakhand, Madhya Pradesh, and Manipur also face erosion rates above the critical limit (NAAS, 2017). Therefore, site-specific best management practices should be identified to bring the prevailing erosion rates within the permissible limits in these areas.

In addition, wind erosion occurs over 14.28 M ha of the land, contributing to 15.66% of the total land degradation in India. Wind erosion occurs in the arid and semi-arid regions of India, especially in Rajasthan (hot desert), Ladakh (cold desert), and Haryana. Wind erosion also occurs in Tamil Nadu, Punjab, Andhra Pradesh, Gujarat, and Odisha to a lesser extent. It causes considerable loss of surface soils rich in nutrients equivalent to $4\,g\ C\ kg^{-1}$ and $0.37\,g\,N\,kg^{-1}$ of soil in Rajasthan (Santra et al., 2013). Therefore, it is necessary to consider effective management practices that can help to retain soil health and also support the crop/grassland productivity in the arid ecosystem.

Tropical cyclones (high winds, intense rainfall, terrestrial flooding, and storm surges) are natural disasters that causes devastating hazards in the coastal regions of world. Effects vary depending on the origins of the storms and the locations of landfall. About 5% of global tropical cyclones originate in the Bay of Bengal, but adjacent countries, including Bangladesh, India, and Myanmar, experience more than 75% of the global casualties (Alam & Dominey-Howes, 2014; Burman et al., 2013). The Bay of Bengal is more turbulent and the epicenter of frequent devastating cyclones, sea surges, and so forth. A huge amount of damage occurs when thousands of hectares of fertile agricultural land and adjoining areas become a wasteland owing to ingress of saline sea water. The sea water increases soil pH and soil salinity and stagnates for a long time, making the land unsuitable for cultivation (Debnath, 2013; Mitra et al., 2020). Analysis of cyclone impacts in coastal areas in India has been reported by many researchers (Thakur et al., 2018; Parida et al., 2018, Mandal et al., 2019). Mishra et al. (2022) reported that the cyclone Nisarga in 2020 caused the shoreline along the coastal zone of Maharashtra to erode by 56.3%.

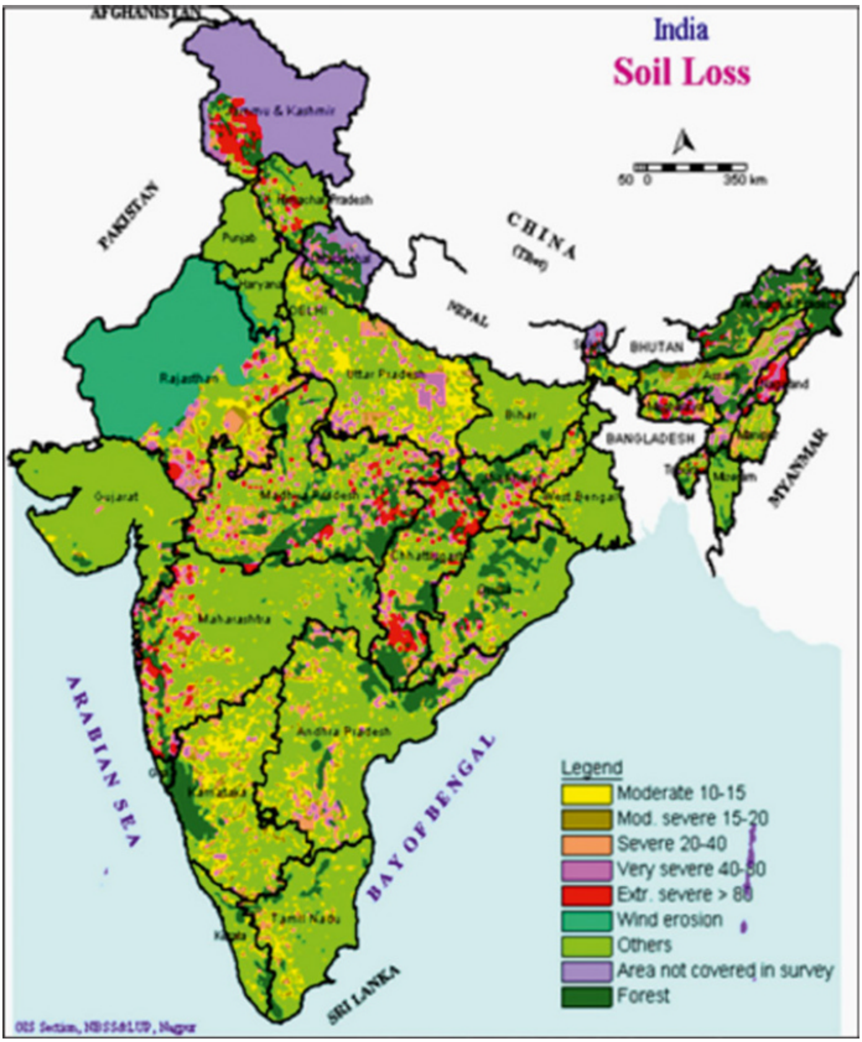

Figure 1.2 Average annual gross erosion rate in different states of India.

Development of Salt-Affected Soils

Salt-affected soils cause major constraints in sustainable food production system of the world. In India, approximately 6.727 million ha of land (2.956 million ha under saline and 3.771 million ha is sodic) has salt-affected soil (Arora et al., 2016; Arora & Sharma, 2017). This land is in the states of Gujarat (2.23 million ha), Uttar Pradesh (1.37 million ha), Maharashtra (0.61 million ha), West Bengal (0.44 million ha), and Rajasthan (0.38 million ha; Mandal et al., 2018) and in four major agriculturally important ecological regions (semi-arid Indo-Gangetic alluvial tract, arid and semi-arid tracts, peninsular regions, and coastal-alluvial region). In addition, approximately 0.3 Mha is characterized as acid sulfate soils (in Kerala and the Andaman and Nicobar group of islands), which have a pH of <4.

Table 1.3 shows the distribution of salt-affected soils in India.

Table 1.3 Distribution of Salt-Affected Soils in India.

State	Sodic soils	Saline soil	Coastal saline soils	Total
Gujarat	14.3	71.2	37.1	32.9
Uttar Pradesh	35.6	1.3	—	20.3
Maharashtra	11.2	10.4	0.6	9.0
West Bengal	—	—	35.4	6.5
Rajasthan	4.7	11.4	—	5.6
Tamil Nadu	9.4	—	1.1	5.5
Andhra Pradesh	5.2	—	6.2	4.1
Haryana	4.8	2.9	—	3.4
Bihar	2.8	2.8	—	2.3
Punjab	4.0	—	—	2.2
Karnataka	3.9	0.1	—	2.2
Orissa	—	—	11.8	2.2
Madhya Pradesh	3.7	—	—	2.1
Andaman & Nicobar Islands	—	—	6.2	1.1
Kerala	—	—	1.6	0.3
Jammu and Kashmir	0.5	—	—	0.3
Total[a]	100 (3.78)	100 (1.71)	100 (1.25)	100 (6.74)

[a] Values in parentheses indicate total area in millions of hectares. *Source:* Adapted from Mandal et al. (2018).

Another major degradational problem in semi-arid tropical areas under rainfed agriculture is regressive pedogenic processes that lead to the formation of pedogenic $CaCO_3$ and concomitant development of subsoil sodicity. These problems affect major soil types in India in the Indo-Gangetic plains, arid and semi-arid regions of western and central India, and the peninsular region in the southern India (Pal, 2019). The largest area under sodic soils (35.6%) occurs in the state of Gujarat. The fundamental mechanism in the precipitation of pedogenic $CaCO_3$ in the semi-arid tropical environment is water loss through evapotranspiration. In clay-rich soils of semi-arid central India, pedogenic $CaCO_3$ formation results in the simultaneous development of sodicity throughout the soil depth. The accumulation of soil inorganic carbon in terms of pedogenic $CaCO_3$ production in soils has been seen as a curse since it reduces soil productivity (Srivastava et al., 2002; Bhattacharyya et al., 2004; Pal, 2019). The creation of pedogenic $CaCO_3$ in an arid climate raises the pH and the relative quantity of Na^+ ions in both soil exchange sites and solution, causing the fine clay particles to disperse. Pedogenic $CaCO_3$ development generates a chemical condition that allows clay particles to deflocculate and travel downward. Therefore, due to these two simultaneously occurring pedogenic processes, the relative amount of sodium and the soil pH increase with depth.

Soil salinity commonly occurs in arid environments, particularly in desert soils where intense evaporation leads to high salinity levels. This is especially true in inland river basins with relatively high water tables. Despite salinity effects not always being immediately apparent, crop yields can still suffer. Desert soils, primarily composed of sandy soil (90%–95%), are found in low-rainfall regions and are characterized by low nitrogen and organic matter content, but high levels of calcium carbonate and phosphate, making them infertile (Moharana et al., 2021). The calcium content in the lower soil layers is 10 times higher than in the topsoil. In India, desert soils cover about 4% of the total area and are found in regions such as Rajasthan, parts of Punjab and Haryana between the Indus and the Aravallis, the Rann of Kuchchh in Gujarat, and coastal areas of Orissa, Tamil Nadu, and Kerala (https://en.wikipedia.org/wiki/Desert). These soils are prone to wind erosion and support low population densities.

The largest area of saline soils (71.2%) is found in the state of Uttar Pradesh. Over 72% of coastal saline soils are located in the states of Gujarat and West Bengal. Increased soil salinization is due to (a) increased demand for water, (b) increased evaporation (c) increased salt accumulation in crops via increased transpiration, and (d) rising sea water level causing increased saline water intrusion. Moharana et al. (2019) have reported the development of secondary salinity and salt migration in the irrigated areas of upland, medium land, lowland, and wetlands of Indira Gandhi Nahar Pariyojna (IGNP) that have also caused changes in the land use from dry lands crops to irrigated crops.

Waterlogged Soils

Excess soil water leading to waterlogging is one of the major causes of land degradation in India, rendering agricultural land sub productive. Factors contributing to waterlogging are faulty water management in the agricultural sector, disparity between the inflow and outflow of irrigated water, and improper drainage systems, among others. The expansion of irrigated areas over the years has exacerbated the problem, with inadequate drainage having led to increased waterlogging in agricultural lands. Additionally, excess monsoon rains cause seasonal waterlogging in low-lying areas. Soil is considered waterlogged when surplus water stagnates due to poor drainage or when a shallow water table rises, saturating soil pores in the crop root zone. This saturation restricts normal air circulation, decreases oxygen levels, and increases carbon dioxide levels, altering the physical, chemical, and microbiological properties of the soil. Approximately 11.6 Mha, or 8.3% of India's net sown area, are waterlogged (Planning Commission, 2011), with over 20% of this area in the eastern region, where surface waterlogging is a major issue. Eastern India, particularly the 15 eastern districts of Uttar Pradesh, all districts of Bihar and West Bengal, and parts of Odisha, constitutes a significant portion of the Ganga Meghna-Brahmaputra basin, home to 500 million of the world's poorest people (Saxena NC, Planning Commission). State-wise break up of the areas affected by water is presented in Table 1.3.

The introduction of canal irrigation through the Indo-Gangetic Plains has brought about significant improvements, including enhanced micro-climate conditions, changes in land use and cropping patterns, and better soil moisture conditions. However, prolonged irrigation using surface flow methods has also led to several issues such as rising water table levels, waterlogging, marshland formation, increased soil salinity, and reduced biodiversity. The expansion of canal irrigation has been linked to widespread waterlogging and salinity problems in various areas (Pandey, 2013). Effective regulation of waterlogging can be achieved through methods such as raised bed farming, mechanical drainage (both surface and sub-surface), bio-drainage, and controlled irrigation measures. Examples of effective bio-drainage plants include *Syzygium cumini*, *Pongamia pinnata*, *Terminalia arjuna*, *Casuarina glauca*, and *Eucalyptus tereticornis*. Additionally, using tolerant or resistant crop varieties and proper nutrient management can enhance the survival of agricultural crops in waterlogged soils.

Acid Soils and Acid Sulfate Soils

Globally, 3,950 Mha of arable land are affected by soil acidity (Ultisols or Oxisols with a pH of 5.5 or lower), including approximately 1,043 Mha of farmland in Asia. This includes 5 Mha in the Near East, 212 Mha in the Far East, 314 Mha in Southeast Asia and the Pacific, and 512 Mha in North and Central Asia (Sumner & Noble, 2003; Osman, 2018). In India, about 28% of the TGA is affected by acidity to varying degrees (Maji et al., 2012). Highly acidic soils in India are primarily found in the Himalayan ecosystem, the red and lateritic regions of the southern and eastern plateau, and some pockets in the greater plains. Soils with pH values below 4.5 cover only 1.9% of India's TGA, amounting to approximately 6.24 Mha. Moderately acidic soils with pH values ranging from 4.5 to 5.5 cover 24.4146 Mha, or 7.4% of the TGA. As noted by Mandal et al., (2023), acid soil occurrence is higher in the Himalayan ecosystem owing to rainfall conditions. The Eastern Himalayan ecosystem, which includes the Northeastern region and parts of sub-Himalayan West Bengal and Jharkhand, has more extensive acid soil areas compared with the Western Himalayan region, covering Uttarakhand, Himachal Pradesh, and Jammu and Kashmir. Peninsular India and some coastal areas, particularly in Tamil Nadu, Kerala, Karnataka, and Goa, also have acid soils. Analysis of the acid soil map of India shows that the total area of highly acidic soils (strongly and moderately acidic) amounts to 30.6572 Mha, which is 9.3% of the TGA. Arunachal Pradesh has the largest extent of strongly acidic soils, followed by Manipur, Sikkim, Tamil Nadu, Kerala, Chhattisgarh, Nagaland, Tripura, and Assam. Chhattisgarh has the largest area of moderately acidic soils (5.93 Mha), followed by Kerala (2.78 Mha), Assam (2.33 Mha), Arunachal Pradesh (1.74 Mha), Nagaland (1.48Mha), Manipur (1.43 Mha), Mizoram (1.26 Mha), and Meghalaya (1.18 Mha). Other states have less than 1,100 hectares of moderately acidic soils. Acidic soils are not found in Haryana, Punjab, Rajasthan, Gujarat, and Delhi.

If left unmanaged, soil acidity can negatively affect soil quality and plant growth. Acid soils are generally low in available phosphorus and exchangeable bases such as potassium and calcium. They also have low base saturation, low cation exchange capacity, and high levels of potentially toxic elements such as aluminum, iron, and manganese. Consequently, the productivity of acid soils is very low ($<1\,t\,ha^{-1}$) due to deficiencies in phosphorus, calcium, magnesium, molybdenum, and boron and the toxicity of aluminum and iron. The availability of boron decreases in acid soil due to its adsorption on sesquioxide, iron, and aluminum hydroxy compounds. Kaolinitic and illitic clay minerals dominate acid soils. Soil pH affects the bioavailability of plant nutrients and indirectly influences crop growth. Therefore, managing acid soil should focus on improving its production potential through amendments or adjustments in agricultural practices to achieve optimum yields under acidic conditions. Even within crops, variety performance can vary under acidic conditions. Acid soils can be managed by growing crops suitable for particular soil pH (acid-tolerant crops), ameliorating soils with inorganic amendments (lime, phosphogypsum) or organic amendments (farmyard manure, poultry manure, pig manure, green manure, biochar), and adopting good agronomic practices (crop scheduling, crop diversification, lime application techniques, seed priming, integrated nutrient management, growing multi-purpose tree species, agro-forestry systems, adding crop residues) to counteract soil acidity (Majumdar et al., 2022).