Soil Biology

Bhupinder Pal Singh
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Soil Health and Climate Change

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Soil Biology

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Soil Health and Climate Change

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Preface

There is growing consensus among the scientific community that global warming caused by increased concentration of greenhouse gases in the atmosphere is one of the most serious environmental problems facing the world today. It is estimated that global mean surface temperature could rise over 6°C by 2100. In addition to global warming, increased greenhouse gas concentrations may increase the occurrence of precipitation extremes: greater precipitation is expected in already-wet areas and increased drought in already-dry areas. Furthermore, widespread expansion of industry and agricultural activities may increase atmospheric nitrogen deposition to unprecedented levels, which will modify climate change impacts. Climate change is also expected to increase the severity and frequency of wildfire, floods, and pest and pathogen attacks. These global environmental changes will pose serious consequences for the overall functioning of terrestrial ecosystems, particularly for agriculture and forestry.

Soil is an important component of terrestrial ecosystems that support life on the earth; it serves as a buffer medium for perturbations to biogeochemical processes of importance to global climate change, acts as a source or a sink for greenhouse gases, and thus underpins social, economic and environmental well-being of humans. Many of the ecosystem services provided by soils are reliant on organic matter. It is therefore critical that land is managed to increase soil organic matter, which will assist in halting rising atmospheric [CO_2], improving soil structure, and decreasing soil erosion and land degradation. In view of changing climate, it is vital that soil health is maintained because a healthy soil is able to sustain physical, chemical and biological functions, and recover following perturbations, due to inherent resilience. A healthy soil enhances plant productivity, promotes plant, animal and human health, maintains water and air quality, supports a diverse community of soil organisms, and resists stresses of human impact and climatic perturbations, so resists environmental degradation. A healthy soil is a complex dynamic living resource that is resilient as a result of its capacity for self-organisation. “Soil health” is thus a broad term, encompassing physical, chemical and biological characteristics, which may be assessed through quantitative measures and also qualitatively expressed indicators. The terms “soil health” and “soil quality” are both used in the literature to describe the capacity of a soil to contribute to ecosystem functions, meet human needs and bear stresses. In this book, we use these two terms synonymously.

Several books on the topic of soil health or soil quality have been published over the last two decades, mainly with a focus on assessing soil health/quality indicators or soil functions in relation to managing soil health in terrestrial ecosystems under existing climatic regimes. The principal objectives of this book are to: (i) present a comprehensive overview of responses of key soil properties or processes to potential impacts of climate change; (ii) highlight the importance, for major conventional and emerging land use systems, of maintaining soil health to mitigate and adapt to climate change impacts; and (iii) describe soil-related feedback processes with implications for plant productivity and climate change. A better understanding of the influences of global environmental changes and land management on soil health is important for ensuring sustainable agro-ecosystems, developing adaptive strategies and sustaining the capacity of soil to meet demands for food, fibre, fodder, timber, and fuel for present and future generations.

Part I provides an overview of the concept of soil health, highlighting the role of soil carbon sequestration for improving soil health and mitigating and adapting to potential impacts of climate change. This section also provides a review of current knowledge about physical, chemical and biological indicators of soil health within the context of climate change and their significance for monitoring impacts of land management and climate change on soil health. Part II focuses on important soil attributes and processes including soil structure, soil pH, soil organic matter, nitrogen cycling, soil respiration and soil biota, and their responses and/or their role in sustaining the environmental functions of soil ecosystems under future climate change scenarios. Part III considers a range of conventional land use systems such as cropping, pastoral, forestry and rangeland, as well as rehabilitated mine-sites, with focus on managing soil health and the processes in these systems that can help to mitigate and adapt to climate change impacts. In Part IV, special attention is given to describing emerging management systems such as organic farming, biochar and bioenergy, and the impact of these systems on soil health and climate sustainability.

With contributions from internationally renowned experts, this book will be a great knowledge resource on the topical area of "soil health and climate change". We believe the book will interest students and researchers in soil, plant and environmental sciences, as well as policy makers and industry stakeholders involved in natural resource management, agricultural development and climate change mitigation through land use management. The compiled information is expected to generate stimulating discussions among scientists and will assist in formulating research aiming to tackle knowledge gaps identified by the contributors.

We thank the authors for their contribution to this volume and appreciate their diligence in responding to reviewers' comments, thereby ensuring high standards. All chapters have been peer-reviewed as per the standards of international scientific journals, and we are thankful to reviewers for providing critical assessment and suggestions that helped in improving the chapters. Last but not least, we also

express our thanks to the series editor, Prof. Ajit Varma, and the publisher for providing us the opportunity to edit this book.

Sydney, NSW, Australia

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Part I
Soil Health Indicators for the Climate Change

Chapter 1
Soil Health and Climate Change: An Overview

Rattan Lal

1.1 Introduction

Soil health refers to the capacity of soil to perform agronomic and environmental functions. Important among these functions are: agronomic/biomass productivity, response to management and inputs, and resistance to biotic and abiotic stresses. With reference to agricultural land use, soil health refers to its capacity to sustain and support growth of crops and animals while also maintaining and improving the environment. Such definitions of soil health imply an integrated holistic or system-level approach, and are based on the concept that the whole is bigger than sum of its components. Key components include soil properties, processes, and synergistic interactions among them. An integrated approach considers soil as a living system which responds to managerial interventions as does an organism (Kibblewhite et al. 2008). It is in this context that the concept of soil health is similar to that of human health (Magdoff 2001), and is determined by maintenance at an optimum level of key soil properties and processes. Key soil properties important to maintaining good soil health include favorable soil texture and structure or tilth, good internal drainage, optimal water, and nutrient retention capacities and soil reaction. Relevant soil processes include good aeration, low susceptibility to erosion, and strong nutrient cycling. An optimal level of soil organic matter (SOM) content is essential to all key soil properties and processes, which are strong determinants of soil health. To be in good health, a soil must also be relatively free from pests and pathogens including nematodes and weeds, and have adequate nutrient reserves and suitable elemental concentrations and balance. A healthy soil must also have strong resistance to degradation processes and able to recover following a perturbation because of inherent resilience (Magdoff 2001). The term "soil health" is primarily used by farmers, land managers, extension agents, and other practicing professionals.

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Table 1.1 Parameters to measure soil quality/soil health and express soil health

Quantifiable soil quality parameters	Qualitative soil health characteristics
Particle size distribution	Texture. feel
Water stake aggregation, mean weight diameter	Tilth, cloddiness
Pore size distribution and total porosity	Internal drainage
Water retention capacity	Droughtiness, inundation
Erodibility	Prone to erosion
Infiltration capacity/rate	Time to ponding
pH	Taste, smell
Cation/anion exchange capacity	Buffering
Electrical conductivity	Salinity
Nutrient concentration and availability	Fertility
Soil organic carbon concentration	Color, smell
Microbial biomass carbon	Biodiversity
Time to recover/restore following disturbance	Resilience

In comparison, the term "soil quality" is used by soil scientists and ecologists (Herrick et al. 1999; Karlen et al. 2003). In this book, are used these two terms synonymously. Soil health denotes numerous functions and ecosystem services provided by a soil. Important among ecosystem services are net primary production (NPP), denaturing, and filtering of pollutants to purify water, improving air quality by scrubbing contaminants, enhancing the environment, and moderating climate at local, regional, and global scales. Therefore, soil quality is assessed by identifying and measuring some key parameters (Table 1.1; see Chap. 2). Parameters used as indicators of soil health are similar to those used for assessing soil quality. However, parameters are assessed and characterized qualitatively for soil health and quantitatively for soil quality (Table 1.1). Because of a strong similarity and often interchangeable use of these terms, several indices of assessing soil quality are also used to assess soil health (Table 1.2). Soil health is assessed using a composite soil health index and several biological indicators (Table 1.2). These key parameters are specific to three distinct but interrelated components: physical, chemical, and biological (Fig. 1.1). The strong interaction among these components (i.e., biophysical, biochemical, and physicochemical) determines soil quality/soil health. However, the same parameters are also relevant to denote soil health, although used in somewhat descriptive and qualitative terms. The term "soil quality" is used under both natural and managed ecosystems, while "soil health" is used for soils managed to grow crops and pastures. Management, characterization, and knowledge about SOM pool are equally important in describing soil health or assessing soil quality. Cycling of carbon (C) through atmosphere–plant–soil continuum, and its transformation and retention among these components (Fig. 1.1), is important to soil health. The C cycle is also important to gaseous composition of the atmosphere, the global climate change, and quality of water as moderated by fate and transport of pollutants and sediments.

Most of the indicators of soil health listed in Table 1.2 are specific to land use or soil management functions. There are only few indices of generic application.

Table 1.2 Assessment of soil health at different scales

Soil	quality/health index	Scale	Application	Reference
1.	Composite soil health index (CSHI)	Field plots	Assess impact of tillage, rotation	Idowu et al. (2009)
2.	Soil biological quality	Field plots	Response to crop management	Gil et al. (2009a, b)
3.	Holistic assessment of soil quality	Landscape	Urban ecosystems	Schindelbeck et al. (2008)
4.	Soil quality index (SQI)	Watershed	Impact of conservation practices	Karlen et al. (2008)
5.	Short-term indicators	Landscape	Mulch management for vegetables	Mochizuki et al. (2008)
6.	Soil biological quality	Field plot	Impacts of pesticides	Korthals et al. (2005)
7.	Soil health dynamic	Field plot	Rotation and cover crop impacts	Carter et al. (2003)
8.	Biological indicators	Field	Organic farming impact	Stockdale and Watson (2009)
9.	Biological indicators	Landscape	Rainfed farming, tree crops	Moreno et al. (2009)
10.	Chemical and biological parameters	Field	Impact of organic farming	Van Diepeningen et al. (2009)
11.	Soil organic carbon	Field	Agricultural land use	Farquharson et al. (2003)

The soil quality index (SQI) by Karlen et al. (2008) is of a wider application. It is based on integration of soil physical, chemical, and biological properties and processes. Several biological indicators (Farquharson et al. 2003; Stockdale and Watson 2009) are specific to organic farming. The index by Schindelbeck et al. (2008) is specifically designed for urban ecosystems. The Cornell Soil Health Index (Gugino et al. 2009) is applicable to arable and urban ecosystems. Other soil quality indices have been proposed by Andrews et al. (2004) and Lal (1994).

The objective of this chapter is to: (1) describe the processes, factors, and causes influencing soil health, (2) discuss the importance of soil organic C (SOC) pool and its management on soil health, and (3) explain the significance of soil C sequestration in off-setting anthropogenic emissions, mitigating climate change by atmospheric enrichment of CO_2 and other greenhouse gases (GHGs), and adapting to possible climatic disruptions through enhancement of soil's buffering capacity.

1.2 Soil Health and Human Health

The strong link between soil health and human health, although known to ancient civilizations, is neither widely recognized nor adequately understood. Indian and Chinese literature has documented the impact of iodine (I) on human health for four to five millennia. Yet, the topic is undervalued by policy makers and planners, often

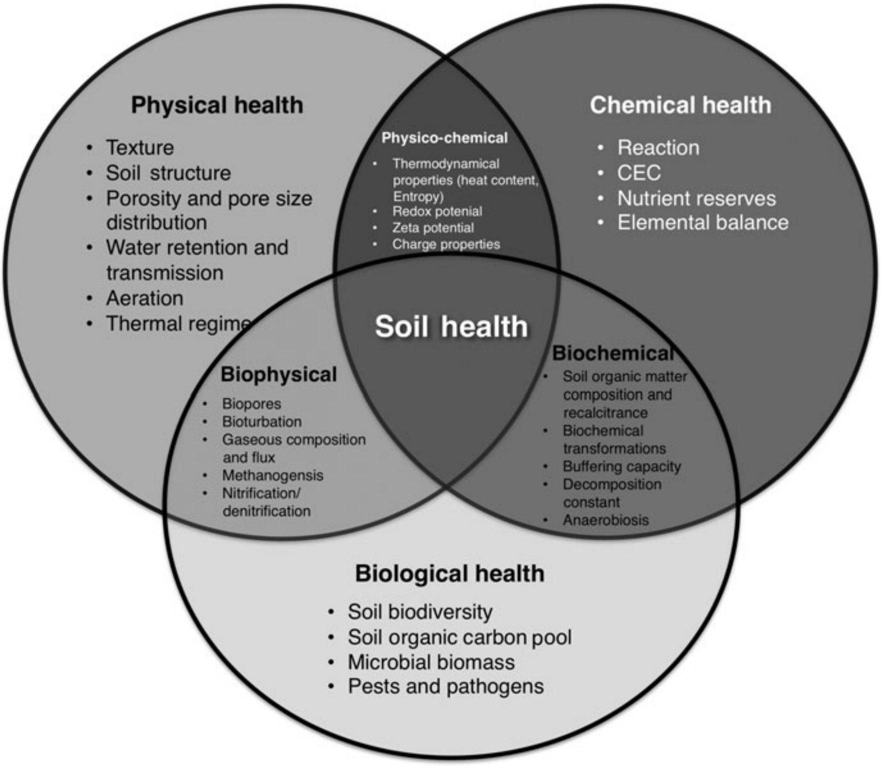

Fig. 1.1 Components of soil health

with severe consequences. For example, food insecurity perpetuates in regions with the highest rate of soil degradation such as in Sub-Saharan Africa and South Asia (Abrahams 2002). In addition to the amount of food production (e.g., cereals, food legumes, roots and tubers, milk and animal products), the quality of food is also strongly impacted by soil health. Important aspects linking soil health with human health through quality of the food produced are the concentrations of micronutrients (i.e., I, Fe, Se, CO, Cr, Cu, F, Mn, Mo, Zn, Ni, Si, V), protein, and essential amino acids in agronomic produce. Soil health can affect human health through deficiency, excess, or imbalance of some of these elements in soils. Soil health also affects human health through its effects on the dietary intake and the environment (Marlow et al. 2009).

The close interaction between soil health, human heath, and environmental quality is depicted in Fig. 1.2. Environmental impacts of soil health are related to its interaction with the hydrosphere that alters water quality, biosphere that moderates NPP and nutrient/elemental uptake, lithosphere that affects stability of the landscape (seismic activities, landslides), and the atmosphere that affects global climate change through alterations in the concentrations of GHGs and other airborne contaminants (e.g., soot, particles, pathogens). The strong link between soil

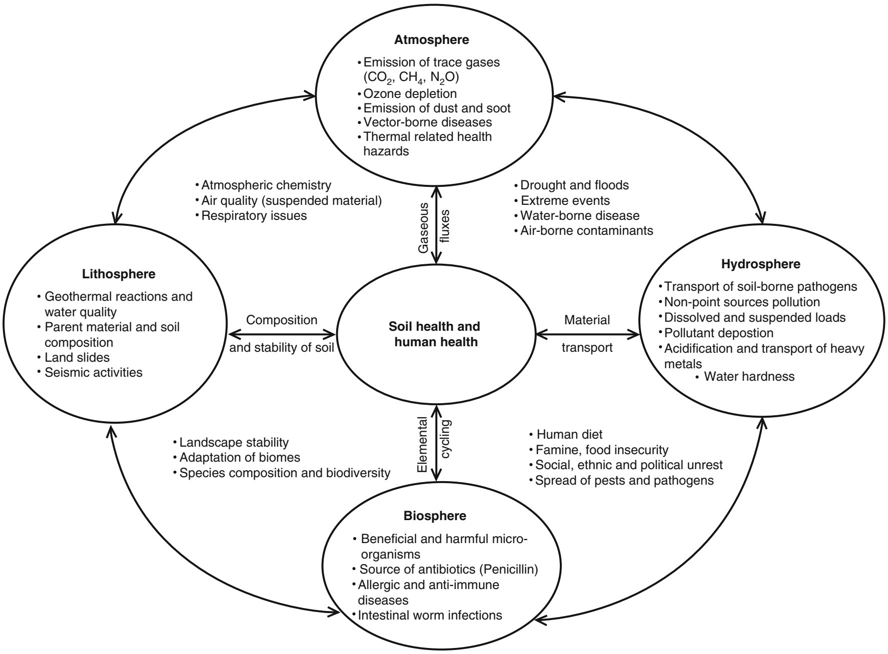

Fig. 1.2 Indirect effects of soil health on human health through interactions with the environment

health and global climate is moderated through storage and emission of carbonaceous (CO_2, CH_4, soot), nitrogenous (N_2O, NO_x), and other organic and inorganic compounds. How humans manage soils influences the production and emission of these gases. The magnitude of gaseous emission is also influenced by the prevailing climate. Thus, there is a positive feedback relating gaseous emissions from soils to changing climate. Climate change and global warming may affect human health through shifts in the geography of vector-borne diseases such as malaria, dengue, and chistosomiasis (Abrahams 2002). Changes in weather patterns may also exacerbate food and water shortages, increase the thermal-related mortality, and aggravate respiratory problems.

1.3 Soil Erosion and Gaseous Emissions

Soil erosion is a four-step process: detachment, transport, redistribution, and deposition. Soil detachment is caused by the kinetic energy of raindrop, overland flow, and wind velocity. The breakdown of aggregates and the detachment of particles are relatively more by wind-driven rain than by drops impacting soil in a windless rain. The kinetic energy from these and other agents of erosion disrupts aggregates and exposes the SOC/SOM, hitherto encapsulated and protected, to microbial/

enzymatic reactions. Thus, breakdown of aggregates increases the rate of SOM decomposition. Aggregate breakdown is also exacerbated by transport and the attendant rolling action along with the shearing force of overland flow and blowing wind. The rate of decomposition is also accentuated by erosion-induced changes in soil temperature and moisture regimes, especially on summit and shoulder slope landscape positions. Under these conditions, erosion accentuates emissions of CO_2 (and also of CH_4 and N_2O) from soil to the atmosphere (Lal 2003). In contrast to the increase in decomposition of SOM during the first three phases of the erosional process (i.e., detachment, transport, and redistribution), SOC transported into aquatic ecosystems and buried in depressional sites is protected against decompositions and is sequestered (Stallald 1998; Van Oost et al. 2007). The net effect of accelerated erosion, as influenced by the four-step process, is increase in emission of GHGs from soil to the atmosphere. Lal (2003) estimated the erosion-induced CO_2 emission of 1.1 Pg C/year globally and 15 Tg C/year in the USA. Thus, adoption of conservation-effective measures and restoration of eroded/degraded/desertified soils (see Chaps. 5 and 9) have a large technical potential to sequester C and mitigate the greenhouse effect.

1.4 Restoring Soil Health in Managed and Disturbed Ecosystems

Choice of strategies for managing soil health depends on the land use, antecedent soil properties, the desired function of interest to humans, and the required ecosystem services. Key soil properties and processes that impact soil health in agricultural, urban, and mine land ecosystems are outlined in Fig. 1.3. Three components of soil health (i.e., physical, chemical, and biological) are also important to sustainable management of croplands and grazing/pasture lands (see Chap. 2). Soil physical health depends on texture, structure, rooting depth, drainage, available water capacity, erodibility, and heat capacity which moderates soil temperature. Determinants of soil chemical health include soil pH, nutrient reserves, surface charge properties, salt concentration and electrical conductivity, and elemental balance. Soil biological health is fundamental to microbial transformations of biomass C into humus and fluxes of GHGs into the atmosphere. Key determinants of soil biological health are magnitude of the SOC pool and its composition, microbial biomass C, soil biodiversity, and prevalence of soil-borne pathogens. In agricultural ecosystems, the goal of soil health management is to maintain and enhance agronomic productivity and economic profitability, and the strategy may differ among land uses and cropping systems (Bell et al. 2007).

Urban ecosystems are gaining importance because of the strong increase in urban populations at global scale. Urban agriculture is also gaining importance because of the need for growing more food locally and creating productive landscapes (Pearson et al. 2010). The multifunctional use of urban green space is

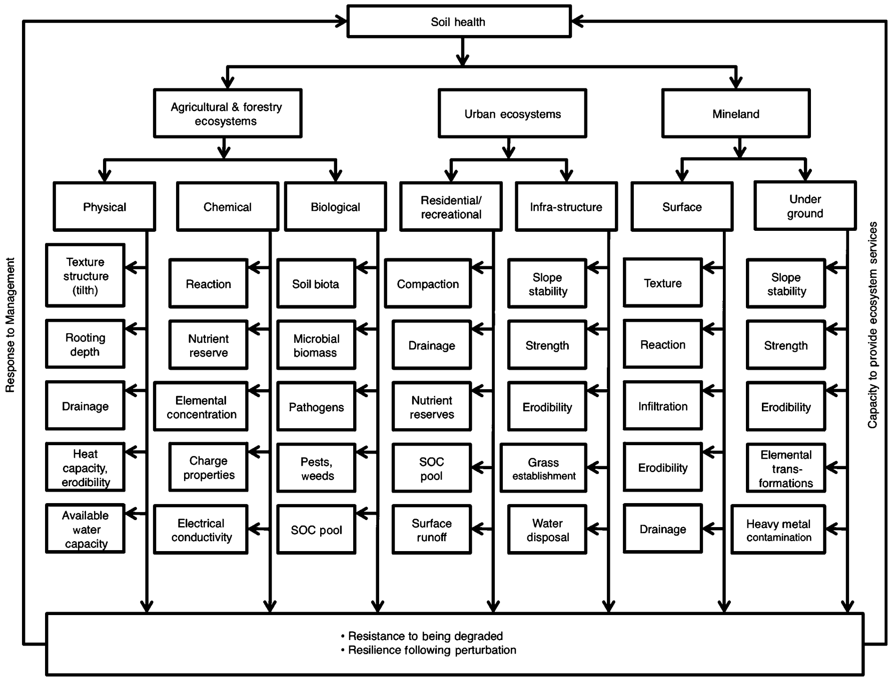

Fig. 1.3 Concepts of soil health for specific land uses and functions

widely recognized (Van Leeuwen et al. 2010). Home lawns and recreational lands, although intensively managed with relatively high inputs, have a large technical potential of soil C sequestration of ~1 Mg C/ha/year (Qian and Follett 2002). Management of landscape for infrastructure (roads, parking areas, airports, etc.) is also important to environments and especially to water quality (Fig. 1.3). Strategies of soil health management comprise sustainable management options for resources including soil, crop, water, and micro-climate (Fig. 1.4).

In addition to advancing food security by growing more grains (cereals and legumes) and roots/tubers (cassava, yam, sweet potato, taro), there is also an increasing interest in producing organic food (Lynch 2009). The goal of organic farming is to develop farm enterprises that are sustainable and harmonious with the environment (Heckman 2006; Srivastava et al. 2007; Watson et al. 2002; see Chap. 14). Organic farming involves adoption of production systems based on reducing external inputs and prohibiting use of synthetic fertilizers, chemical pesticides, and genetically modified organisms (Mason and Spaner 2006; see Chap. 14). Thus, there is a strong reliance on the use of organic nutrient sources for crop production (Rosen and Allan 2007; Srivastava et al. 2009), such as animal manure (Alves et al. 2006; Evanylo et al. 2008), green manure (Chaphale and Badole 1999; Fageria 2007; Khan et al. 2000), residue management and mulch farming (Govaerts et al. 2007; Iqbal et al. 2008; Kachroo et al. 2006; Kornecki et al. 2006;

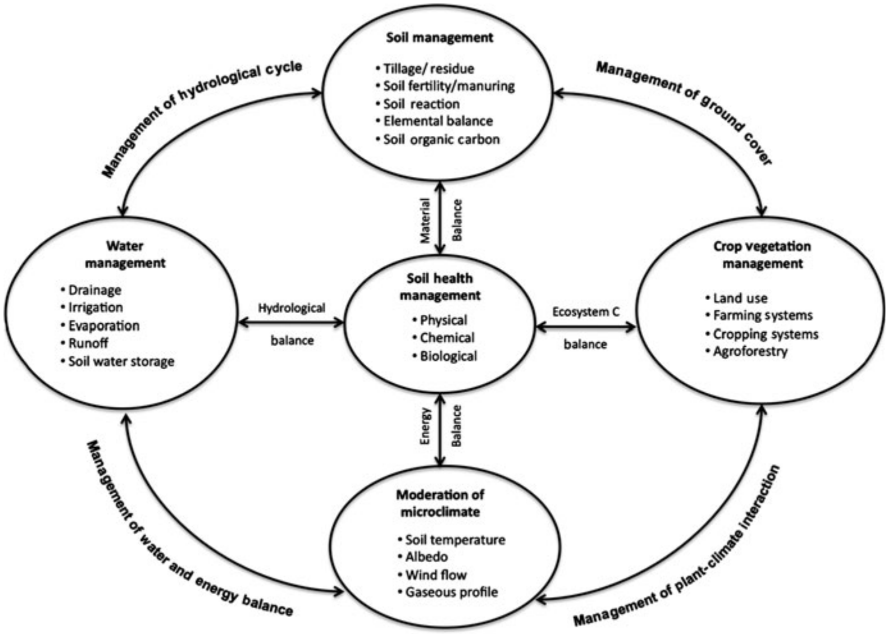

Fig. 1.4 Strategies of soil health management

Lal et al. 2004; Wuest et al. 2000), and use of crop rotations and forages in the rotation cycle (Entz et al. 2002; Katsvairo et al. 2007; Oddino et al. 2008). There is also a growing interest in conservation agriculture (CA) as a system to improve soil health (Burman et al. 2004; Govaerts et al. 2007, 2008; Kassam et al. 2009; Paday et al. 2008; Peiretti 2004; Rainford 2008; Thomas et al. 2007). The goal is to improve soil health through environmentally based practices (Fageria 2002; Narwal 2002). Assessing the environmental impact of organic farming entails measurement of: (1) SOC pools and its dynamics, (2) soil and plant biodiversity, (3) use efficiency of energy, water, and nutrients, (4) nutrient cycling, and (5) emission of GHGs and the attendant impact on climate change (Lynch 2009). In view of the growing population and increasing global food demand, principal constraints to adoption of organic farming are low crop yields due to severe soil nutrient deficiency and high competition from weeds. Yet, organic farming may have specific niches even in densely populated countries of South Asia (Ramesh et al. 2005) because of an increasing public awareness of environmental and health issues. Furthermore, incorporating organic amendments in soil (e.g., manure, compost) and use of residue mulch can suppress soil-borne pathogens, nematodes, and root diseases (Abawi and Widmer 2000). Bailey and Lazarovits (2003) observed that these practices influence pathogen viability and disruption and release of those biologically active substances (from both crop residues and soil microorganisms) that suppress diseases (e.g., root rot in cereals). In this context, long-term use of organic amendments can lead to development of disease-suppressive soils because of improvements in soil's biological health. Thus, some relevant indicators of soil's biological health within organic farming systems include: (1) high biological activity and soil biodiversity, (2) amount and quality of SOC pool, and (3) soil resilience against tillage and mechanical weed control measures. Stockdale and Watson (2009) outlined four principles of organic farming: (1) sustain and enhance the health of the soil, plant animal, human, and planet, (2) strengthen living ecological systems and cycles, and work with them, emulate them, and sustain them, (3) ensure fairness with regard to the common environment and life opportunities, and (4) protect the health and well being of current and future generations and the environment (see Chap. 14).

1.5 Agronomic Strategies of Soil Health Management

In addition to the use of organic amendments (mulching with crop residues), other agronomic strategies of soil health management include conversion to no-till (NT) farming and CA, adoption of integrated nutrient management (INM) involving liberal use of manures and compost, and frequent use of cover crops and green manures in complex crop rotations (Table 1.3). These strategies have proven useful for a range of soils, crops, and eco-regions throughout the world, especially when these have been specifically adapted under site-specific situations. A notable example of improved agronomic practices are those developed for the rice–wheat system (Balasubramanian et al. 2007; Channabasavnna et al. 2002) which were the basis of the "green revolution" in Asia that is continuing to deliver productivity benefits (Table 1.4). Rice, a semi-aquatic plant usually cultivated under submerged conditions, is now increasingly being grown under aerobic environments (Bouman et al. 2007). Water scarcity, especially under dryland farming in arid and semi-arid environments, has necessitated the use of waste and brackish/saline water for irrigation (Tabatabaei and Najafi 2004, 2009), and management of saline soils (Rengasamy 2005). High salinity waste water can also be used for irrigation (Kahlown and Azam 2003) and with drip irrigation technology (Ali 1997).

1.6 Soil Health and Climate Change

Atmospheric concentration of CO_2 has increased by 39% from 280 ppm in the preindustrial era to 390 ppm in 2010, and the present concentration exceeds the range observed over the last 65,000 years (IPCC 2007). Increase in the concentration of CO_2 and other GHGs (CH_4, N_2O) has increased the global mean temperature by $0.76 \pm 0.19°C$ over the twentieth century (IPCC 2007), and with the business as usual, increase in global temperature by the end of the twenty-first century may be $4 \pm 2°C$ with severe adverse impacts on biomes and the ecosystems services.

Table 1.3 Agronomic strategies for soil health management

Technique	Country	Soil	Crop	Impact	References
1. Mulching/residue management	Canada	–	Potato	Suppressing soil-borne diseases	Bailey and Lazarovits (2003)
	Pakistan (Punjab)	Sandy clay loam	Corn	Increase SOC concentration, soil moisture storage and crop yield	Pervaiz et al. (2009)
	India (AP)	Alfisols	Sorghum	Improved soil biological quality (microbial biomass)	Sharma et al. (2008)
	India (Meghalaya)	Inceptisols	Vegetables	Improved soil biological quality (earthworms)	Das et al. (2008)
2. No-till/conservation agriculture	Australia	Limited resource areas	Rice	Improve SOC pool and soil quality	So et al. (2001)
	Australia (Qld)	Vertisols	Sugarcane	Improve sugarcane yield, and decreased detrimental soil biota	Pankhurst et al. (2003)
	Australia (Qld)	Vertisols	Grain crops	Erosion control, water quality, improvement	Silburn et al. (2007)
	Mexico (Central)	Cumulic Phaeozen	Maize, wheat	Increase soil C, infiltration rate, and soil microflora	Govaerts et al. (2007)
	Chile	Ultisols	Wheat–lupin	Improve microbial biomass C and N concentrations	Alvear et al. (2005)
	Canada	Orthic Podzol	Potato	Suppress soil-borne pathogens, improve soil structure	Carter et al. (2009)
	USA (Washington)	Aridisols	Grain crops	Reduce soil erosion, conserve water, improve soil health	Huggins and Reganold (2008)
	India	Alluvial	Wheat	Raised bed system, furrow irrigation	Singh et al. (2009)
3. Manuring/organic farming	Canada	–	Grain crops	Lower crop yields	Lynch (2009)
	India	Vertisols	Soybean, wheat	High microbial biomass C	Behera (2009)
	India	Vertisols/alfisols	Grain crops	Higher SOC pool and microbial biomass C	Vineela et al. (2008)
	USA (IA)	Loess	Vegetables	Better soil quality, higher profit	Delate (2002)
	Turkey	–	Lettece	Lower weeds, higher yields	Isik et al. (2009)
	Holland	–	Grain crops	Higher SOC pool and better soil quality	Van Diepeningen et al. (2006)

4. Forages, cover crops/green manure, rotations	West Africa	Alfisols	Grain legumes	Enhance soil fertility	Odion et al. (2007)
	India	Inceptisols	Wheat–cowpeas	High N-use efficiency	Yadav et al. (2003)
	Italy	–	Meadows, fodders	Weed control	Tomasoni et al. (2003)
	Japan	–	Green pea/wheat	Higher microbial activity	Zai et al. (2008a, b)
	India	Inceptisols	Sebsania in rice	Improved SOC and N pools	Ramesh and Chandrasekaran (2004)
	Philippines	Mahas clay	Mung bean in rice	Better soil health and more labile C	Shrestha et al. (2002)

Table 1.4 Agronomic practices to improve soil health and productivity

Technique	Cropping system	Country	Impact	References
1. Mulching	Rice–wheat	India	Increase water use efficiency, and yield of wheat, weed control; enhanced SOC pool, microbial biomass C, and microflora; improved soil microbial count and soil biological quality	Singh et al. (2008) Pal and Jat (2004) Jat et al. (2004, 2009)
2. Waste water	Sugarcane	Colombia	Better physicochemical quality parameters	Madera et al. (2009)
	Grain crops	India	Lower microbial biomass C and higher respiration rate	Masto et al. (2009)
	Lettuce	Ghana	Increased soil contaminants and health risks	Seidu et al. (2008)
	–	Japan	Increase in denitrification, high salt, and NO_3 concentrations	Shigemastu et al. (2008)
	Maize	Pakistan	Altered soil chemical, bacterial and VAM population	Faryal et al. (2007)
	Cotton, cereals (mixed)	Syria	Waste water treatment is recommended to reduce risks	Ryan et al. (2006)
3. Saline/ brackish water	Fodder	India	Yield reduction, increase in Na^+ uptake	Yadav et al. (2003, 2007)
	Tomato	Iran	Drip irrigation system is recommended	Aminipouri and Ghoddousi (1997) Gil et al. (2009a, b)

Soils have been a major source of atmospheric CO_2 and other GHGs (i.e., CH_4, N_2O) ever since the dawn of settled agriculture (Ruddiman 2003, 2005). The magnitude of CO_2-C emission from soil to the atmosphere since the industrial revolution (~1750 AD) is estimated at 78 ± 12 Pg (Lal 1999). Most soils under agricultural land use contain lower SOC pool than their counterpart under natural/ undisturbed ecosystems because of: (1) lower amount of biomass and detritus material returned, (2) higher decomposition rate attributed to changes in soil temperature and moisture regimes, (3) more leaching losses of the dissolved organic C (DOC), and (4) severe losses by accelerated wind and water erosion. Indeed, there is a large flux of CO_2 from the oxidation of SOM from agricultural soils. Thus, most cropland soils have lost 25–75% of their original SOC pool. In Australia, SOC losses of up to 60% have been reported (Bell et al. 2007; see Chap. 9). The loss of SOC pool is more from soils of the tropics than temperate or boreal climates, with coarse (sandy) than fine (clayey) texture, characterized by high internal drainage than those of slow permeability, and low resilience and high susceptibility to degradation (e.g., erosion, nutrient depletion, salinization) than those of high resilience and low vulnerability. The magnitude of loss is also more from soils managed by extractive farming practices (i.e., residue removal, low or no external input of organic or inorganic fertilizers) than those managed by sustainably intensive methods of crop and animal production. Soil health in managed ecosystems is strongly impacted by the magnitude of SOC loss due to historic land use and soil/crop/pasture management practices. Soil health is adversely affected when the SOC level declines below the critical/threshold range. The range of critical level, varying among soils and climates, may be 1.0–2.0% in the topsoil layer (Aune and Lal 1998).

The magnitude of SOC pool and the rate of its decomposition depend on temperature and precipitation (see Chaps. 5 and 7). Therefore, the projected global warming and precipitation extremes may decrease the global SOC pool. Some soils of the boreal and arctic regions (i.e., Cryosols, Histosols) and peat lands which are now a net sink of atmospheric CO_2 may become a major source because of the positive feedback (Baird et al. 2009). In addition to CO_2, agricultural ecosystems are also source of CH_4 (i.e., rice paddies, livestock, manure management) and N_2O (i.e., fertilizers, manuring, biomass burning). These gases have more radiative forcing and higher global warming potential (GWP) than CO_2. Future climate warming may increase emissions of these gases from soils to the atmosphere.

Sustainable management of soil health is an important strategy for climate risk management through adaptation to climate variability (Baethgen 2010). Good soil health can moderate climatic disruptions through (1) reducing emission of CO_2 and other GHGs, and (2) sequestering CO_2 and oxidizing CH_4. The strategy is to convert agriculturally marginal soils to a restorative land use, and adopt recommended management practices (RMPs) on good soils to create a positive C budget such that $C_{input} > C_{output}$. Restorative land uses include establishing a perennial vegetative cover through afforestation, conversion of cropland to pastures with low stocking rate and controlled grazing, and reclamation and rehabilitation of degraded and desertified soils/ecosystems. Because of the severe depletion of the SOC pool, degraded soils have the highest sink capacity for sequestering atmospheric CO_2. Strategies of C_{input} include use of conservation agriculture with crop residue mulch and cover cropping, integrated nutrient management with liberal use of compost and manure in conjunction with chemical fertilizers and organic amendments, and complex cropping/farming systems involving forages and agroforestry. Processes leading to C_{output} from the soil involve losses by accelerated erosion, mineralization or decomposition, and leaching. The projected climate change may exacerbate the losses by erosion, decomposition, and leaching. Therefore, adoption of RMPs must be actively promoted to off-set the losses by enhancing C_{input} into the system (see Chap. 5). In addition to off-setting CO_2 emissions by sequestering C in the pedosphere, soils of a good health may also cause greater oxidation of CH_4 and reduce N_2O emission by moderating both processes of nitrification and denitrification.

The rate of soil C sequestration differs widely among soils, eco-regions, land uses, and management practices. Examples of some proven management practices to enhance SOC pool and improve soil health are listed in Table 1.5. The potential of SOC sequestration is high in desertified and degraded soils (Lal 2001).

Table 1.5 Management practices to enhance soil organic pool and improve soil health and mitigate climate change

Country	Soil	Management practices	Reference
India	Inceptisols	Crop residue management, organic amendments	Mandal et al. (2007)
USA	–	Corn stalk return, no-till	Hooker et al. (2005)
	Alfisols	Mulch	Duiker and Lal (1999)
Australia	Vertisols	Stubble management, fertilization, no-tillage	Farquharson et al. (2003)
China	Black soils (Mollisols)	Manure, rotations, straw management	Liu et al. (2003)
	Alluvial (Yangtze Plains)	Manure, crop residues, conservation tillage	Rui and Zhamg (2010)
UK	–	Conservation agriculture, straw management	Hazarika et al. (2009)

In general, the rate of SOC sequestration is higher in cooler than warmer climates and humid than arid regions. The rate of SOC sequestration is also more in soils of heavier than lighter texture, and in those with slow or poor than rapid or excessive internal drainage. On a global scale, the rate of SOC sequestration through adoption of RMPs is 300–500 kg/ha/year on croplands and 100–300 kg/ha/year on grazing lands or rangelands (see Chap. 5). The rate of SOC sequestration through afforestation of degraded soils (eroded, salinized, depleted of nutrients), especially in humid and subhumid regions, may be as much as 1,000 kg/ha/year. The net rate of sequestration must be adjusted for C emissions from farm operations and inputs (Lal 2004b). Technical potential of SOC sequestration in world soils is 3–4 Pg/year over ~50 years (Pacala and Socalow 2006), which has a drawdown capacity of reducing atmospheric CO_2 concentration by 50 ppm by 2150 AD (Hansen et al. 2008). Furthermore, C sequestration in soils and terrestrial ecosystems is highly cost-effective and an economic alternative (McKinsey and Co 2009). However, some have argued that estimates of SOC sequestration are highly optimistic (Schlesinger 1999, 2000).

The SOC concentration also improves adaptation to climate change by enhancing soil health and its buffering capacity. Enhancement of the SOC concentration, beyond the critical or threshold range, enhances soil health by: (1) improving soil structure and tilth, (2) enhancing plant available water capacity and reducing droughtiness, (3) increasing soils resistance to erosion and reducing erodibility, (4) increasing nutrient retention and availability, (5) increasing water infiltration rate and reducing surface runoff, (6) improving water quality and reducing nonpoint source pollution, (7) increasing soil biodiversity by providing food and habitat for soil biota, (8) reducing sedimentation in waterways and reservoirs, (9) improving use efficiency of inputs, and (10) increasing crop/plant growth and yield. It is also the improvement in soil health through SOC sequestration that is essential to increasing agronomic production (Lal 2004a) and advancing food security (Lal 2006).

1.7 Soil Resilience and Soil Health

Resilience is defined as the capacity to recover from a perturbation while retaining structure, function, identity, and feedbacks (Brand and Jax 2007; Holling et al. 2002; Lal 1997; Walker et al. 2004, 2010; Walker and Salt 2006). A resilient system is characterized by limits or thresholds and tipping points. Change beyond a threshold level in key properties and processes can lead to a tipping point with an attendant change in state. A soil with low resilience can degrade into another state because of the alterations in key soil properties and processes beyond the critical threshold. For example, decline in soil depth by accelerated erosion, decrease in SOC concentration to below the critical range of 1.1%, increase in electrical conductivity beyond 4 ds/m, and decrease in air porosity to <0.1 (Aune and Lal 1998) can drastically alter soil health with adverse impacts on agronomic production and other ecosystem services.

Resilience and transformability, essential attributes of a good soil, depend on soil health. In the context of changing climate and other perturbations, building soil resilience is essential to coping with external changes and meeting growing demands of increasing world population. Soils of good health, with high SOC concentration and favorable properties and processes (physical, chemical, biological) have high resilience. The strategy is to enable soils to recover and adapt rather than resist a change. Adaptability is essential for a soil to be resilient. Defining threshold levels of key soil properties, specific to land uses and ecosystems, is essential to managing and enhancing soil resilience (Lal 1997).

1.8 Eco-Efficiency and Soil Health

The term eco-efficiency, first used at the 1992 Rio Earth Summit for implementing Agenda 21, implies achieving more with less (Keating et al. 2010). With reference to agricultural ecosystems, the term eco-efficiency implies enhancing quantity and quality of agricultural produce with lower input of land, nutrients, water, energy, labor, etc. It also means slower depletion of soil's inherent fertility comprising the SOC pool, nutrient reserve, topsoil depth, etc. In agronomic terms, eco-efficiency is measured as crop productivity per unit area, time and input. It is also measured in terms of productivity per unit decline in SOC pool, topsoil depth, CEC, nutrient reserve, microbial biomass C, etc.

Considering the need of feeding 9.2 billion people by 2050 with limited availability of soil and water and competing uses for natural resources, it is important to identify, develop, validate, and use eco-efficient approaches to enhance agronomic production. The strong relationship between agronomic yield and SOC concentration in the root zone is widely recognized (Lal 2010). Such a relationship between agronomic yield and SOC concentration is especially strong in low-input (extractive farming) agriculture practiced by resource-poor and small-land holders of the tropics and subtropics. Increasing SOC pool in these systems enhances eco-efficiency through improvements in: (1) soil structure and tilth, (2) water retention, (3) nutrient retention, (4) biotic activity and species diversity, (5) erosion control, etc. (Lal 2010). The eco-efficiency can be improved by minimizing soil erosion, conserving water in the root zone, recycling plant nutrients, optimizing soil temperature regime, creating positive C budget, and enhancing soil resilience. Two among several examples of eco-efficient systems are presented by Kapkiyai et al. (1999) from Kenya and Wani et al. (2003) from Central India. In Kenya, Kapkiyai and colleagues demonstrated that agronomic productivity was enhanced from 1.4 Mg/ha/year in traditional systems to 6.0 Mg/ha/year with RMP, which also enhanced the SOC pool in the root zone from 23.6 Mg/ha to 28.7 Mg/ha over 18-year period. In Central India, Wani et al. (2003) reported from a 30-year study that adoption of RMPs increased productivity from 1.1 Mg/ha/year to 5.1 Mg/ha/year along with SOC sequestration of 330 kg/ha/year. The yield gap, difference in agronomic yield under on-station vis-à-vis under on-farm conditions, that exists throughout the developing countries can be abridged by enhancing eco-efficiency of production systems. Improving soil health, through enhancing SOC concentrations and quality, can also enhance eco-efficiency of production systems (Lal 2010).

1.9 Conclusions

Soil health, capacity of a soil to produce agronomic and economic goods and services while also maintaining the environment quality, is a term used by farmers and land managers. In comparison, the term soil quality is used by soil scientists, agronomists, and pedologist. Key indicators of soil health, similar to that of soil quality, are soil structure, soil organic carbon concentration and quality, water retention and intake rate, and soil biodiversity (see Chap. 2). Thus, maintaining and enhancing these soil properties above the threshold/critical levels are essential to sustaining/improving soil health. Enhancing the soil organic carbon pool also improves agro-ecosystem resilience, eco-efficiency, and adaptation to climate change. Technical potential of soil C sequestration through improvement in soil health is ~3 Pg/year for about 50 years with a drawdown capacity of reducing atmospheric CO_2 concentration by 50 ppm over the twenty-first century. Improving soil health, through restoration of degraded/desertified soil and adoption of RMPs, is also a necessity to feeding the world population of 9.2 billion by 2050.

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