Innovations in Landscape Research

Elmira Saljnikov
Lothar Mueller
Anton Lavrishchev
Frank Eulenstein *Editors*

Advances in Understanding Soil Degradation

Springer

Innovations in Landscape Research

Series Editor

Lothar Mueller, Leibniz Centre for Agricultural Landscape Research (ZALF), Müncheberg, Brandenburg, Germany

Aims & Scope

The Springer series "Innovations in Landscape Research" presents novel methodologies and technologies to understand, monitor and manage landscapes of the Anthropocene. The aim is to achieve landscape sustainability at high productivity. This includes halting degradation of landscapes and their compartments, developing cultural landscapes, and preserving semi-natural landscapes. Clean water and air, fertile and healthy soils for food and other ecosystem services, and a green and bio-diverse environment are attributes of landscapes for the survival and well-being of humans who inhabit them.

How do landscapes function? How do future landscapes look like? How can we sustainably develop intensively used and stressed kinds of landscapes? Scientific innovations and decision tools are key to answer and solve those challenging questions. The series will inform about advanced methods and results of disciplinary, interdisciplinary and transdisciplinary work in landscape research. It presents a broad array of methods to measure, assess, forecast, utilize and control landscapes and their compartments. These include field and laboratory measurement methods, methods of resource evaluation, functional mapping and risk assessment, and sensing methods for landscape monitoring, advanced methods for data analysis and ecosystem modeling, methods and technologies for optimizing the use of multi-functional landscapes, for the bioremediation of soil and water, and basics and procedures of landscape planning. The series provides a new view on landscapes with some focus on scientific and technological innovations, on soils and problems of optimizing agricultural landscapes under conditions of progressive urbanization. Landscape research in a globalized world of the Anthropocene is based on gathering big data and scenario modeling. International long-term experiments and agri-environmental monitoring systems will deliver data for ecosystem models and decision support systems.

Edited volumes of this series will address the following topics at high priority: Status and Trends of Landscape Research; Understanding Key Landscape Processes; Landscape Services, Functions and Biodiversity; Assessing Soil Resources and Quality; Water Resource and Quality Monitoring; Landscape Monitoring Concepts and Studies; Landscape Sensor and Monitoring Technologies; Landscape Modeling and Decision Support; Agricultural Soil and Plant Management; Basics and Tools for Landscape Planning; Tools for Water and Wetland Management; Forest Management and Agroforestry; Rehabilitation of Degraded Landscapes.

The books of this series are a source of information for researchers, teachers, students, and stakeholders interested in the topics of landscape science and related disciplines. They present status analyses, methodical chapters and case studies showing the practical relevance and feasibility of novel decision tools and technologies. Thus, the books of this series will be a particular valuable information basis for managers and decision makers at various levels, from local up to international decision bodies.

An author/editor questionnaire, instructions for authors and a book proposal form can be obtained by contacting the Publisher.

More information about this series at https://link.springer.com/bookseries/16118

Elmira Saljnikov • Lothar Mueller •
Anton Lavrishchev •
Frank Eulenstein
Editors

Advances in Understanding Soil Degradation

Springer

Editors
Elmira Saljnikov
Department of Pedology
Institute of Soil Science
Belgrade, Serbia

Anton Lavrishchev
Department of Soil Science
and Agrochemistry
Saint-Petersburg State
Agrarian University
St. Petersburg, Russia

Lothar Mueller
Leibniz Center Agricultural
Landscape Research
Müncheberg, Brandenburg, Germany

Frank Eulenstein
Leibniz Centre for Agricultural
Landscape Research
Müncheberg, Brandenburg, Germany

ISSN 2524-5155 ISSN 2524-5163 (electronic)
Innovations in Landscape Research
ISBN 978-3-030-85681-6 ISBN 978-3-030-85682-3 (eBook)
https://doi.org/10.1007/978-3-030-85682-3

© The Editor(s) (if applicable) and The Author(s), under exclusive license to Springer Nature Switzerland AG 2022
This work is subject to copyright. All rights are solely and exclusively licensed by the Publisher, whether the whole or part of the material is concerned, specifically the rights of translation, reprinting, reuse of illustrations, recitation, broadcasting, reproduction on microfilms or in any other physical way, and transmission or information storage and retrieval, electronic adaptation, computer software, or by similar or dissimilar methodology now known or hereafter developed.
The use of general descriptive names, registered names, trademarks, service marks, etc. in this publication does not imply, even in the absence of a specific statement, that such names are exempt from the relevant protective laws and regulations and therefore free for general use.
The publisher, the authors and the editors are safe to assume that the advice and information in this book are believed to be true and accurate at the date of publication. Neither the publisher nor the authors or the editors give a warranty, expressed or implied, with respect to the material contained herein or for any errors or omissions that may have been made. The publisher remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

This Springer imprint is published by the registered company Springer Nature Switzerland AG
The registered company address is: Gewerbestrasse 11, 6330 Cham, Switzerland

Contents

Understanding Soils: Their Functions, Use and Degradation

1

Elmira Saljnikov, Frank Eulenstein,
Anton Lavrishchev, Wilfried Mirschel,
Winfried E. H. Blum, Blair M. McKenzie,
Linda Lilburne, Jörg Römbke, Berndt-Michael Wilke,
Uwe Schindler, and Lothar Mueller

Abstract

Soils, the thin skin of the earth, a living body, are the basis of all highly developed life and have ensured human existence and culture since millennia. Their functions and ecosystem services are crucial for the survival of humanity. Increasing pressure on soils through overuse and mismanagement has exceeded their capacity to perform, which is considered as soil degradation. To meet the mission of the Sustainable Development Goals of the United Nations, soil degradation must be stopped and reversed. We reviewed framework conditions of soil degradation, scientific concepts of research and status and trends of their operationalization. Soil performance and degradation processes must be understood, monitored, mitigated and combated in the context of different categories and scales such as ecosystems, land and landscapes. Approaches to the assessment and monitoring of soil dynamics, degradation and desertification show inconsistencies and knowledge gaps at several levels. Concepts of soil health and ecosystem services of soil

---

E. Saljnikov (✉)
Institute of Soil Science, Teodora Drajzera 7, 11000
Belgrade, Serbia
e-mail: elmira.saljnikov@soilinst.rs

E. Saljnikov · F. Eulenstein · U. Schindler
Mitscherlich Academy for Soil Fertility (MITAK),
GmbH, Prof.-Mitscherlich-Allee 1, Paulinenaue,
14641 Brandenburg, Germany
e-mail: feulenstein@zalf.de

U. Schindler
e-mail: schindler@mitak.com

F. Eulenstein · W. Mirschel · L. Mueller
Leibniz-Centre for Agricultural Landscape Research
(ZALF), Eberswalder Str. 84, 15374 Müncheberg,
Germany

A. Lavrishchev
St. Petersburg State Agrarian University,
Peterburgskoye Ave. 2, 196601 St. Petersburg,
Pushkin, Russia

W. E. H. Blum
Institute of Soil Research, University of Natural
Resources and Life Sciences, Peter-Jordan-Str. 82,
1190 Vienna, Austria
e-mail: winfried.blum@boku.ac.at

B. M. McKenzie
Geography and Environmental Science, University
of Dundee, D1 4HN Dundee, Scotland, UK
e-mail: b.mckenzie@dundee.ac.uk

L. Lilburne
Manaaki Whenua—Landcare Research, PO
Box 69040, Lincoln, Canterbury, New Zealand
e-mail: lilburnel@landcareresearch.co.nz

J. Römbke
ECT Oekotoxikologie, GmbH, Böttgerstr. 2–14,
65439 Flörsheim, Germany
e-mail: j-roembke@ect.de

B.-M. Wilke
Department of Ecology, TU Berlin, BH 10-1,
Ernst-Reuter-Platz 1, 10587 Berlin, Germany
e-mail: bmwilke@tu-berlin.de

E. Saljnikov et al. (eds.), *Advances in Understanding Soil Degradation*,
Innovations in Landscape Research, https://doi.org/10.1007/978-3-030-85682-3_1

should be backed by "hard data" based on field and landscape indicators and measurements. Participatory approaches to mediate conflicting demands of stakeholders are crucial for a broad understanding of soil and its long-term sustainable use. This requires an advanced field diagnostic system of soil performance based on reliable on-site measurement technology in combination with expert-based knowledge and assessment methodologies. Strengthening field soil science is essential for progress in reducing and reversing soil degradation.

Keywords

Soil degradation · Soil functions · Ecosystem services · Soil quality · Indicators · Field methods

Abbreviations

AI	Aridity index
CASH	Comprehensive assessment of soil health
CICES	Common international classification of ecosystem services
DEX	Decision EXpert
DPSIR	Driving forces, pressures, states, impacts and responses
DSS	Decision support system
EC	Electrical conductivity
EEA	European environmental agency
ENVASSO	Environmental assessment of soil for monitoring
ES	Ecosystem services
ESAI	Environmentally sensitive area index
EU	European union
FAO	Food and agriculture organization of the united nations
GLASOD	Global assessment of soil degradation
LCA	Life cycle analysis
LRC	Land resource circle concept
MDS	Minimum data sets
M-SQR	Muencheberg soil quality rating
N_2O	Nitrous oxide
NDVI	Normalized difference vegetation index
PCA	Principal component analysis
RUSLE	Revised universal soil loss equation
SAR	Sodium absorption ratio
SDG	Sustainable development goals
SD	Soil degradation
SB	Soil biodiversity
SF	Soil fertility
SH	Soil health
SMAF	Soil management assessment framework
SoilHealthDB	Soil health DataBase
SOM	Soil organic matter (SOM)
SQ	Soil quality
SQI	Soil quality index
UAV	Unmanned aerial vehicle
UN	United Nations
UNCCD	United Nations convention to combat desertification
UNEP	United nation environmental programme
VESS	Visual examination of soil structure
VSA	Visual soil assessment method
WRB	World reference base for soil resources

1.1 Introduction

The world's population grows at an explosive pace. Production of food, fibre and other goods must keep pace with this growth in order to prevent the rollback of humanity and the reduction of the level of well-being of the world's population (Foley et al. 2011). To simply feed the additional billions of people in future, a further unprecedented increase in food production through agriculture is required.

Productive soils are the basis of agriculture. Agriculture in the late Holocene and Anthropocene has required the introduction of modern agricultural technologies based on the widespread use of machinery, fertilizers and pesticides, the latest irrigation methods, etc. (Dobrovolskiy et al. 2012; Mueller et al. 2020). Also, rapid globalization and urbanization, the emergence of many large cities dramatically increased the requirements for the elementary quality of housing, minimally at the level of household and sanitary comfort and transportation. Everywhere, large-scale construction activities, such as urban development, transport and traffic facilities or the creation of reliable sources of water and energy, are needed. All these, and other factors such as climate change, put pressure on all global resources, including agricultural land.

Soils are the most important parts of the global land resource. Soils are the upper layer of the earth, their skin, a living body. They are a result of parent rock, climate, vegetation, organism activities and relief over time and of human activity (Dokuchaev1951; Thorp 1942). Like other natural systems, soils underlie the processes of development, ageing and disturbances (Walker et al. 2010).

Soils have a capacity and resiliency to provide biomass for food, fodder and other ecosystem services to humans and to recycle their waste (Blum 2005; Mueller et al. 2010; Blum and Nortcliff 2013). If the status of soil falls irreversibly beyond these limits of capacity and resiliency, it is considered as degraded.

Understanding the functioning of soils and developing tools for wise decisions of soil management are crucial for meeting the Sustainable Development Goals (SDG) (UN 2015) of the United Nations (Keesstra et al. 2016; Tóth et al. 2018). The World Soil Charter (FAO 2015) supports the achievement of SDGs through principles of understanding and sustainable use of soils. Principle 10 of the World Soil Charter addresses the need to minimize or eliminate soil degradation.

This chapter reviews the main aspects of soil degradation, their causes, triggering factors, consequences and monitoring problems. Attention is paid to degradation caused by anthropogenic impacts through land-use change and agricultural management practices. The chapter also addresses different approaches in assessing the degree and forms of degradation, indicators and attributes of changes in soil quality and health in the context of ecosystem functioning. Processes of soil degradation require better understanding. Knowledge gaps in the reliable assessment of soil degradation and desertification will be identified.

1.2 Soils, Ecosystems and Humans

1.2.1 Pedosphere and Anthroposphere

To understand the mechanisms of soil degradation requires information about soils. Soil is a cornerstone component of pedosphere, which is an intersection of atmosphere, hydrosphere, lithosphere and biosphere. Only in the pedosphere, minerals, organic matter, air and water come into a dynamic complex interaction, thus wonderfully providing and sustaining life on earth.

Entire civilizations can rise and fall depending on the ability of the soil to supply food. The knowledge about soil and its fertility has been accumulated during the last several thousand years in different regions. An especially high level of this knowledge was achieved in the ancient riverine civilizations of Egypt (first irrigation cultivation), Mesopotamia, India and China. Broader knowledge about soil and its treatment was accumulated by farmers and compiled by what might be called the first soil scientists in the Roman empire. In those days, soil fertility was seen as a divine power of the earth and it was worshipped in numerous legends and myths. Traditionally, soil was considered as the natural environment for the growth of terrestrial plants, regardless of its physical structure (e.g. whether it has identifiable horizons or not).

However, even in the earliest agricultural societies, it was known that there is a need of providing “food” such as compost for the soil in order to keep soil fertile. People also recognized the importance of soil not only as a source of food, fibre, medicine and other necessary raw materials but also as a medium for filtering water and recycling wastes.

Between 1877 and 1880, Dokuchaev, the pioneer in soil studies, introduced a new concept of soil. It was defined as an independent natural body, consisting of a high but limited number of types, each with a unique morphology and properties, conditioned by the site-specific combined effects of climate, living organisms, geology, relief and age (Dokuchaev 1951; Trofimov et al. 2020). It was a revolutionary concept, which allowed the consideration of all soil characteristics together, as a complete, integrated natural body, where the effect of one property depends on the combined interactions of other properties in space and time. The Russian view of soils as an independent natural body with genetic horizons has led to the concept that soil is a part of the earth’s crust with properties reflecting the influence of local or regional soil-forming agents. After extended soil expeditions in the nineteenth century, Dokuchaev’s team of researchers concluded that soil fertility decline (i.e. the loss of favourable soil properties) is caused by humans, i.e. an inappropriate land use such as the destruction of the soil layers as well as deterioration of its water regime.

Soil acts as an intermediary for chemical and biogeochemical flows in and out of the whole earth system and consists of gaseous, mineral, liquid and biological components. Soil is a starter and generator of energy flowing through a chain: soils, plants and organisms (microbes and animals). Food chains are the channels of life and by death and decay this energy is returned to the soil, being available for another circle.

With accelerated industrial development, a new anthropogenic influence was added to this interaction. Given that the soil is an integrated part of the network of food, energy and water interactions, it is a functional component of environmental sustainability that is linked to climate change, decline in biodiversity, water, energy and food security (Bouma 2014; Gupta et al 2019).

Soil is considered as a non-renewable resource, since it takes thousands of years for rocks to weather into soils, and hundreds of years for rich organic matter layers to build up. Our welfare depends, to a large extent, on our soils since soil is the end product of the combined influence of climate, topography, organisms (flora, fauna and human) on parent materials (original rocks and minerals) over time.

Since more than 99% of the world’s food is produced via soils, the importance of soil in the food, energy and water nexus is crucial (Pimentel and Burgess 2013; FAO 2019). An increase in the production of food, fibre and bioenergy by increasing soil productivity with the help of new technologies may result in an increased rate of soil degradation up to a critical point when technological progress cannot overcome the limits of degraded and depleted soil (Hatfield et al. 2017).

1.2.2 Soil Functions

The environmental importance of soil is not limited to food production as soil is a multifunctional system (Dobrovolskiy et al. 2012). Blum (2005) divided soil functions into two main domains: ecological functions (biomass production, protection of humans and the environment and gene reservoir) and non-ecological function (physical basis of human activities, source of raw materials and geogenic and cultural heritage). Independently, ecologists have developed the Ecosystem Service Concept (ESS) (Costanza et al. 1997; MEA 2005), which quickly became the main theoretical approach in environmental policies, but which has—at least in the beginning—neglected soils (Dominati et al. 2010). Soil environmental functions include every aspect of life support on the earth, such as primary production, renewable energy and raw material as well as transportation and recycling of water and nutrients. In fact, the decontamination of groundwater and the maintenance of the food chain are among the most important soil environmental functions (Keesstra et al. 2016), which are controlled by the capacity of soil for (1) filtration of solid and liquid compounds, (2) compound buffering via adsorption and precipitation and (3) compound transformation via alteration and decomposition by soil biota (Blum 2005).

Summarizing, the soil functions can be grouped into the following domains (Larson and Pierce 1991; Arshad and Coen 1992; Snakin et al. 1996; Singer and Ewing 2000; Blum and Nortcliff 2013; Bampa et al. 2019), Fig. 1.1:

- Biomass production: medium for plant/crop growth (food, fodder and renewable energy).
- Filtering and buffering organic and inorganic components: ensures healthy food, fodder, water and fibre.
- Gene reserve and environment for the growth and development of biodiversity: plants, animals, and microorganisms contribute to maintaining and improving soil quality.
- Basis for technical, residential and industrial structures and infrastructures: ever-growing population and urbanization inevitable put an increasing pressure on soil quality and accessibility.
- Source of minerals, materials and fossil fuels: intensive mining negatively affects climate change and landscape properties.
- Natural and cultural heritage: contribute to the history of the evolution of life and environment.
- Regulation of biochemical processes:
  The cycling of carbon and nutrients, water and energy through pedosphere, biosphere, atmosphere and hydrosphere by participating in the two cornerstone biochemical processes on earth: photosynthesis and decomposition.
- Regulation of geochemical processes:
  Gas exchange between the pedosphere and atmosphere
  Geochemical runoff into the ocean.

For the area covered by states of the European Union recognizes seven soil functions that are vulnerable to soil threats were identified (FAO and ITPS 2015):

1. biomass production, including agriculture and forestry,
2. storing, filtering and transforming nutrients, substances and water,
3. biodiversity pool, such as habitats, species and genes,
4. physical and cultural environment for humans and human activities,
5. source of raw materials,
6. acting as a carbon pool,
7. archive of geological and archaeological heritage.

Soil enables the function of terrestrial ecosystems (Doran et al. 1996). Every environmental function of soil is directly or indirectly linked with food, energy and water nexus (Adhikari and Hartemink 2016) and is associated with the physical, chemical and biological processes taking place in the soil–water–plant–organism system. Within the soil ecosystem, the microbial and zoological biodiversity is largely unexplored. This requires basic research in order to improve the understanding of soil functioning in general, since it affects all other soil functions significantly (Heintz-Buschart et al. 2020).

1.2.3 Soils for Sustainable Development of Humans in the Anthropocene

The awareness about increasing conflicts between human demands and limited global resources has inspired ideas on how to ensure livelihoods at a better level of sustainability. The Millennium Ecosystem Assessment (MEA 2005) provided a status analysis of global ecosystems based on the concept of ecosystem services (Daily et al. 1997; Costanza et al. 1997). This concept has initiated a broader view of the role of soil in global ecosystems. The Intergovernmental Technical Panel on Soils (FAO and ITPS 2015) has demonstrated this by linking the most important ecosystem services (ES) with soil functions (Table 1.1).

Table 1.1 should be considered as a first step and as an inspiration for more specific definitions

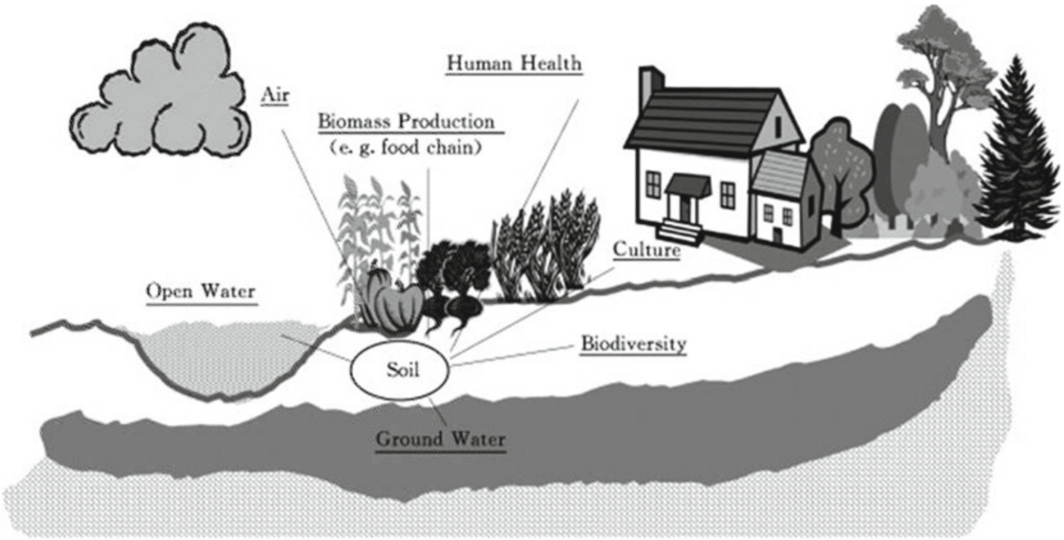

Fig. 1.1 Goods and services are provided by land and soil. 2013 *Source* Blum (2012)

and quantifications at different levels. A number of specific soil functions and ecosystem services (ES) were not yet mentioned here. This was done in numerous later studies (e.g. Schulte et al. 2014; Schwilch et al. 2018; Drobnik et al. 2018; Van Leeuwen et al. 2019). Soil policies of the European Union (EU) and elsewhere assess soil multifunctionality based on these concepts (Vrebos et al. 2017; Schwilch et al. 2018).

Emerging concepts of ecosystem services are based on theories that consider soils as a natural capital and public good. On the other hand, global tendencies of land concentration in the hands of fewer people, land grabbing, privatization of public land and privatization of public research in agriculture and soil science are on the rise (Mueller et al. 2020). This has led to conflicts and controversial debates in the scientific community with implications for research on how to measure and control soil quality/health and degradation (Wander et al. 2019).

McBratney et al. (2014) introduced the overarching concept of Soil Security. This concept addresses existential global environmental challenges based on soil's performance in the same manner as food security or water security, including the idea of sufficient access to these resources by individuals or communities. They propose five dimensions of Soil Security:

- Capability that relates to maintain the soil in its place in the landscape.
- Condition that relates to the state of the soil, e.g. free from contamination.
- Capital that includes a clear economic value particularly as part of ecosystem service.
- Connectivity that brings in the social aspects of stewardship, management and tenure.
- Codification that aligns with the policy and legislation to protect and enhance soil (McBratney et al. 2014).

This concept requires assessment frames, parameterization and interlinkage with other concepts such as that of ES, but it has the potential to help meet the UN's SDGs (Bouma 2019a). SDG 15 of UN (2015): "Life on Land", explicitly addresses "Sustainably manage forests, combat desertification, halt and reverse land degradation, halt biodiversity loss" (UN 2015), that is a mandate to act.

Table 1.1 Ecosystem services provided by the soil and the soil functions that support these services

Ecosystem service	Soil functions
Supporting services: Services that are necessary for the production of all other ecosystem services; their impacts on people are often indirect or occur over a very long time	
Soil formation	Weathering of primary minerals and release of nutrients
	Transformation and accumulation of organic matter
	Creation of structures (aggregates, horizons) for gas and water flow and root growth
	Creation of charged surfaces for ion retention and exchange
Primary production	Medium for seed germination and root growth
	Supply of nutrients and water for plants
Nutrient cycling	Transformation of organic materials by soil organisms
	Retention and release of nutrients on charged surfaces
Regulating services: benefits obtained from the regulation of ecosystem processes	
Water quality regulation	Filtering and buffering of substances in soil water
	Transformation of contaminants
Water supply regulation	Regulation of water infiltration into soil and water flow within the soil
	Drainage of excess water out of soil and into groundwater and surface water
Climate regulation	Regulation of CO_2, N_2O and CH_4 emissions
Erosion regulation	Retention of soil on the land surface
Provisioning Services: products (“goods”) obtained from ecosystems of direct benefit to people	
Food supply	Providing water, nutrients, and physical support for growth of plants for human and animal consumption
Water supply	Retention and purification of water
Fibre and fuel supply	Providing water, nutrients, and physical support for growth of plant growth for bioenergy and fibre
Raw earth material supply	Provision of topsoil, aggregates, peat, etc
Surface stability	Supporting human habitations and related infrastructure
Refugia	Providing habitat for soil animals, birds, etc
Genetic resources	Source of unique biological material and information
Cultural services: non-material benefits that people obtain from ecosystems through spiritual enrichment, aesthetic experiences, heritage preservation and recreation	
Aesthetic and spiritual	Preservation of natural and cultural landscape diversity
	Source of pigments and dyes
Heritage	Preservation of archaeological records

Source FAO and ITPS (2015)

1.2.4 Soils as Compartments of Land and Landscapes

Neighbour disciplines of soil science such as geography, landscape ecology and agriculture consider soils as a crucial compartment of their central subject of study, such as geosystem, landscape and land, respectively (Hole 1978; Van Eetvelde and Antrop 2005; Amato et al. 2017; Nikiforova et al. 2019).

The categories “land” and “landscape” are broader than “soil”. From understanding of the Food and Agriculture Organization of the United Nations (FAO), “soil” is an essential component of "land" and "ecosystems" where both are wider concepts encompassing vegetation, water and climate in the case of land, and in addition to those three aspects, also social and economic considerations in the case of ecosystems (FAO 2020a). From a definition of the European Environmental Agency (EEA), "Land" commonly refers to the planet's surface not covered by seas, lakes or rivers. It includes the total land mass including continents and islands. In more daily use and legal texts, "land" often refers to a designated piece of land. "It consists of rocks, stones, soil, vegetation, animals, ponds, buildings, etc." (EEA 2020). From understanding of the United Nations Convention to Combat Desertification (UNCCD), land is "the terrestrial bio-productive system that comprises soil, vegetation, other biota and the ecological and hydrological processes that operate within the system" (UNCCD 1994). This is very similar to the operation field of soil science.

"Landscape" is a still broader concept with focus on the interaction between nature and humans at regional and local levels. Antrop and van Eetvelde (2019) characterize the "landscape" as a holistic concept. "As a spatial unit, it characterizes the identity of the land of a community and defines a territory where custom rights apply. Both territory and scenery are manifestations of local, regional or national relationships between a community and the way it is using the environment" (Antrop and Van Eetvelde 2019). Landscape approaches are promising for understanding, monitoring and tackling problems of sustainable use of natural resources, use, degradation and conservation of soils included (Mueller et al. 2019).

To consider soils as parts of landscapes has implications for soil conservation and restoration strategies. Measures of landscape conservation are based on the ES concept and consider soil, land and landscapes as a natural capital (Costanza et al. 1997, 2017; Müller et al. 2015; Grunewald et al. 2015). The Land Resource Circle (LRC) concept, developed by Lilburne et al. (2020) (Fig. 1.2), is a framework, linking soil functions with land and landscape functions to inform users about the suitability and value of a local land parcel.

Soil erosion is a typical example of a complex landscape-related process (Dotterweich 2013). Erosion translocates soils, mainly by wind and water (Figs. 1.3, 1.4, 1.5, 1.6). However, processes are not soil processes only. They depend on landscape attributes (Ouyang et al. 2010), have shaped landscapes over geological periods and have been impacting the survival of humans and civilizations over millennia (Montgomery 2007). Accelerated rates of man-made erosion of soil on agricultural land, about 10–40 times higher than the natural process (Dotterweich 2013), have to be considered as a soil degradation process. Combating processes of accelerated soil erosion that causes harmful off-site effects, such as degradation of drylands and pollution of water in particular, requires approaches at landscape scale (Issanova and Abuduwaili 2017; Boardman et al 2019; Smetanová et al. 2019; Prasuhn 2020).

Changes in the overall economy and socio-economic system of a country or region cause expansion or reduction in the area of cropping land and are a main factor of spatiotemporal alterations in soil degradation. A typical example is Asian Russia, where soil erosion has reduced by about 70–90% in some regions in the last decades as compared with the period of intensive cropping in the 1960–1990th (Litvin et al. 2021). On the other hand, those processes are often associated with a decline of rural regions, and shifts of environmental problems and soil degradation to industrial and urban centres. Abandoned lands can be seen as untapped agricultural potentials whose soil's risks for new cycles of degradation must be minimized (Prishchepov et al. 2020; Frühauf et al. 2020).

1.2.5 Land Use and Stress on Soils

Multifunctional use of land and soils. Soils have experienced alterations, stress and disturbances since the Neolithic Revolution when humans began to settle, to develop agriculture on

Fig. 1.2 The Land Resource Circle (LRC) framework for describing the key soil, land and ecosystem functions of a land parcel. *Source* Lilburne et al. (2020), with kind permission of Elsevier

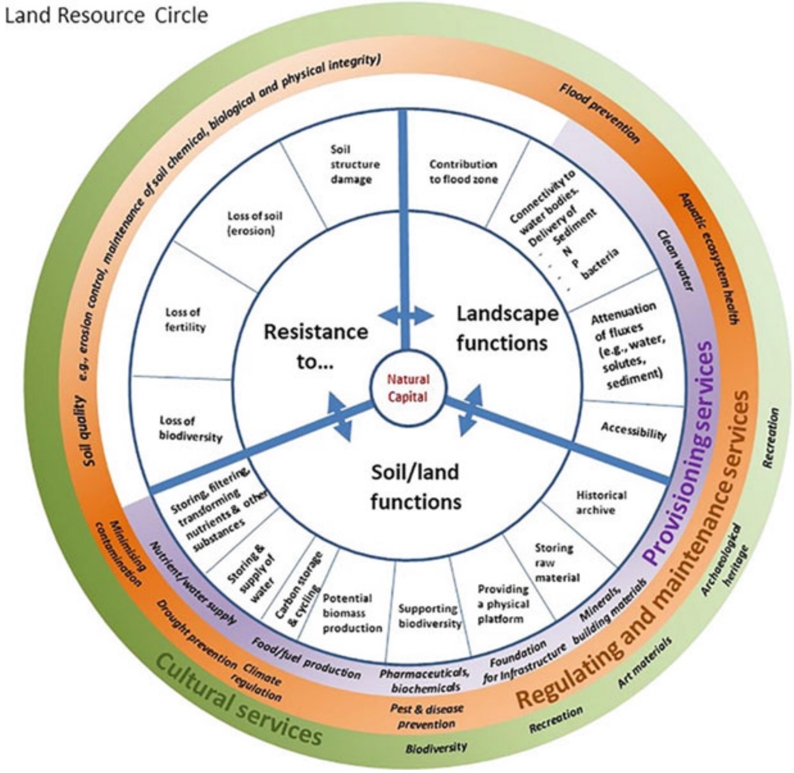

Fig. 1.3 Water erosion as a landscape forming process. Canyon of a tributary of the Charyn river in Kazakhstan (left). Zonal soils are brown desert soils. Dry valley (ovrag) near Kursk, Russia (right). Zonal soils in the region are Chernozems on Loess parent material. Historical erosion removed the Loess down to the Tertiary basis. *Photos* L. Mueller

former grasslands and forests, to dig for minerals and other natural resources for the production of tools and weapons and to develop civilizations and cultural landscapes. These processes accelerated with the increasing size of human populations, ever-increasing division of labour and innovations. Figure 1.7 shows the degrading impacts of human activities on soils.

Currently, in the Anthropocene, the age shaped by humans, soil, land, landscapes and all spheres of the globe are exposed to extreme pressure (Crutzen 2002; Lewis and Maslin

Fig. 1.4 Accelerated soil erosion by water on sloped cropland, considered as a soil degrading process. Canola field in Germany. Denudation field part (left) and accumulation field part (right). Zonal soils in this region are Luvisols and Retisols (Albeluvisols) on Late Pleistocene parent material. New soil types are developing on eroded field parts. *Photos* L. Mueller

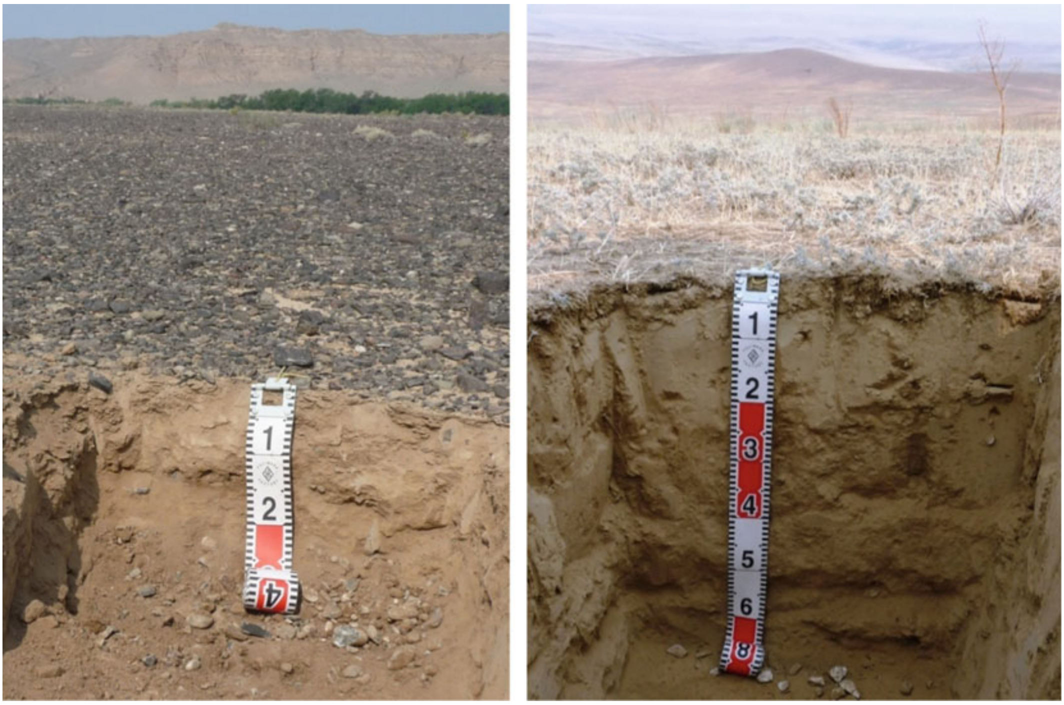

Fig. 1.5 Wind erosion as a landscape forming process. Photos show soil profiles in deserts and semi-deserts of Kazakhstan. Brown desert soil with surface gravel lag (left). Surface gravel accumulation is the result of long-term blowing off of finer soil particles. It reduces further erosion largely, maintaining its potential to re-vegetate. Light Chestnut soil developed on fine sandy aeolian sediments. CIS Alatau region near Almaty (right). Vegetation is degraded grassland/rangeland and, thus, prone to current accelerated erosion, degrading the soil and land. *Photos* L. Mueller

Fig. 1.6 Wind erosion induced by soil tillage on Loess soils as a soil degradation process on cropland of the Columbia Plateau in the Northwestern USA (location near Pendleton, OR). Climate is semiarid. Soils are Kastanozem. Tillage for seedbed preparation. As fine material and organic matter are blown off first, the remaining topsoil became coarser textured and humus depleted. *Photos* L. Mueller

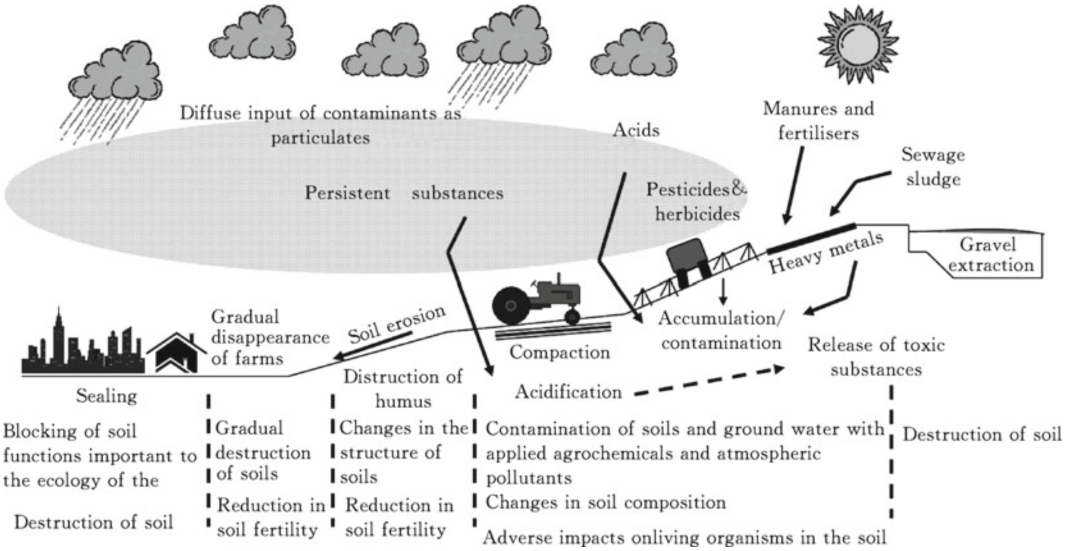

Fig. 1.7 The impact of human activities on soil (*Source* Blum 2008)

2015). Besides agriculture, the focus of soil functioning or destruction is more and more triggered by problems associated with localized extreme overpopulation, such as land transformed by urbanization and the construction of infrastructure, waste disposal, air pollution and others. Meanwhile, all soils and landscapes worldwide carry signs of human activity including “alien” substances (plastic particles, artificial, radioactive and chemical substances, nitrogen and phosphorus loads, etc.), impacting ecosystems in a complex manner (Tarolli et al. 2018).

Pressure on agricultural soils. Since humans started agriculture to meet their basic needs for food and fibre and to improve their livelihoods, they tried to achieve high yields from soil through its intensified management. Problems with insufficient soil performance for food production root back to antiquity. The decline in high natural soil fertility due to agriculture and the resulting drop in crop yields have been significant problems throughout history (Montgomery 2007). Soil and land degradation, erosion, in particular, in Northern Africa, the “grain chamber” of Rome contributed to the collapse of the Roman Empire (Montgomery 2007).

During the 10 thousand years of soil cultivation, agriculture developed gradually with ups and downs, discoveries and inventions. Land-use intensity increased due to increased demands for food, which could only be satisfied by scientific and technological innovations. Over the past 200 years, agricultural science and soil science have developed as acknowledged scientific disciplines (Dickson 1805; Thaer 1809; Körte 1839; Dokuchaev 1951). Since the industrial age, knowledge gains in soil science and plant nutrition speeded up. Innovations based on technological progress and sophisticated agricultural experiments improved fertilizer production and machinery, while at the same time, agricultural decision support and scheduling systems optimized plant and soil resources, thus enabling a rapid growth of agricultural production (Ascough et al. 2002; Bochtis et al. 2014; Dobrovolskiy et al. 2012; Mueller et al. 2020; Poulton and Johnston 2020; Trofimov et al. 2020).

Unfortunately, understanding of ecological problems lags behind the development of science and technology (Kazakov 2019). Despite of much progress in understanding land-use effects on soils, practical problems with decreasing soil performance have increased. Many scientists and more and more informed citizens recognize the crucial importance of soil as the basis of human life. Decision-makers and low-resource farmers, however, often neglect the importance of soil resources due to lack of awareness and/or lack of accessible information or tools and resources (Packer et al. 2019; Tamene et al. 2019).

Negative effects of soil’s overexploitation. In the pursuit to increase land productivity, soil is exposed to a permanent overexploitation of its potential (Fig. 1.7). This has led to a wide range of consequences such as accelerated soil erosion processes caused by deforestation and overgrazing, improper irrigation and tillage (Montgomery 2007; Olsson et al. 2019; Gupta et al. 2019; Gajić et al. 2020); loss of top soil layer due to deflation (Zhu et al. 2020); dissection of the terrain due to rill erosion and gully formation (Guo et al. 2019; Hassen and Bantider 2020); loss of fertility due to nutrient mining and leaching (Gupta et al. 2019; Zhang et al. 2020); contamination due to overuse of pesticides, ameliorants, airborne toxic elements, industrial and urban landfills (Khan et al 2018; Steffan et al. 2018; Huang et al. 2019; Gruszecka-Kosowska et al. 2020; Orlova et al. 2017); loss of biodiversity due to use of agrochemicals, excess tillage (Borelli et al. 2017; Guerra et al. 2020); salinization due to improper irrigation, lack of drainage systems (Abdollahpour et al. 2020; Nguyen et al. 2020), overcompaction due to heavy mechanical loads (Arvidsson and Keller 2007; Schjønning et al. 2016; Parkhomenko et al. 2019) and acidification due to misuse of fertilizer and airborne acidic depositions (Jones et al. 2020; Liu et al. 2020). Furthermore, these impacts might cause off-site effects such as sedimentation, siltation and eutrophication of water bodies or enhanced flooding, reduced watershed function, changes in natural habitats leading to loss of genetic stock and biodiversity.

Another indirect effect of the above-listed impacts is the adverse effect on climate via increased carbon dioxide (CO_2) emissions due to accelerated mineralization of soil organic matter (SOM) (Lal 2004; UNDP 2019; Franko and Witing 2020) and nitrous oxide (N_2O) as a result of land conversion (Borelli et al. 2017). Overall, about half of global land used for agriculture is moderately or severely degraded (UN 2015).

Challenges for soil governance and soil science. Within an 11-year period (from 2001 to 2012) production rate of most common crops increased by 13% (Borelli et al. 2017) due to advanced technologies in land management (Foley et al. 2011) and the increased use of fertilizers (Mueller et al. 2012a, b). Sufficient food production requires sufficient area of both arable and pastoral agricultural land, while production of safe and nutritious food requires healthy, fertile and biogenic soil (Blum and Nortcliff 2013).

The area of fertile soils has been decreasing while the area of degraded soils has been increasing as the world's population is growing, expected to reach 9 billion by 2050. Fertile soils have been irreversibly lost by sealing as part of the expansion of cities and other infrastructure. In general, a higher population density is associated with increasing areas of highly degraded soils (Nachtergaele 2000). Very probably, this will trigger social problems such as "ecological" migrations from the most affected regions to regions with low population densities (Bouma and Bajtes 2000). All these trends pose serious challenges and great responsibility for agricultural policy to reduce the human impact on soil and initiate sustainable land management. Scientific technical innovation and decision tools are demanded to support this process.

1.3 Assessment of Soil Performance

1.3.1 Concepts of Soil Fertility, Soil Quality and Soil Health

Which soil states are considered as regular and well performing, which states need to be considered as degraded and which processes lead to degradation? Answering these questions requires evaluation of concepts of soil performance, including suitable indicators, measurement methods and data, data evaluation scales and thresholds and sustainable technologies of soil management (Blum and Eswaran 2004).

Soil fertility, quality and health are concepts to characterize the performance of soil for meeting its functions for humans. These concepts were developed and became popular in different times and regions, have a different focus in aims and contents, have some overlapping and still coexist.

Soil fertility (SF). Soil fertility is a traditional concept, referring to the ability of soil to sustain plant growth in agriculture. It has been the domain of agricultural plant nutrition and soil science, has been popular for around 100 years, especially in the second half of the twentieth century (Kundler 1989; Patzel et al. 2000). About more than 40 different definitions exist in the German literature (Term: Bodenfruchtbarkeit) of the twentieth century (Patzel et al. 2000), where the degree of human impact on soils and crop yields is the most modifying factor. As harvested crops withdraw nutrients from the soil, their site-specific replacement by fertilization is a key topic of maintaining SF. Soil fertility can also be enhanced through complex practices of fertilization, mechanization, soil water management and best cropping practices (Kundler 1989), leading not only to higher crop yields but to aggradations (e.g. the opposite of degradation) of soil.

Soil quality (SQ). This concept has been developed in the USA and became very popular in the 1990s. As a result of an extended scientific debate, it considered more soil functions than food and fibre production by agriculture. Soil quality is "the capacity of a specific kind of soil to function, within natural or managed ecosystem boundaries, to sustain plant and animal productivity, maintain or enhance water and air quality and support human health and habitation" (Karlen et al. 1997). The broad definition of soil quality includes a potentially wide array of soil functional services, such as environmental, economical, social, physical, biological and chemical. However, in practice, assessment of all soil parameters that relate to these functions is still impossible. Also, no soil is capable of successfully performing all of these functions (Singer and Ewing 2000). Going from the plausible hypothesis that soil quality is a pillar of environmental quality, Bünemann et al. (2018) pledge for a better operationalization of this concept by specifying targeted soil threats, functions and ecosystem services, developing interactive assessment tools with target users, and consideration of biological/biochemical indicators. Sustainable agricultural soil use has also been a main target of practical approaches to quantify SQ. Soil quality and crop yield potentials depend on soil inherent properties, which change very slowly with time such as soil texture and mineral composition, and dynamic properties such as soil structure, which can, in the short term, be influenced by management (Karlen et al. 1997; Mueller et al. 2010).

Soil health (SH). The concept became popular in the wake of the soil quality discussion in the USA in the late 1990s and still dominates the current scientific debate. The soil is seen as a biological system whose health status must be maintained or restored (Sekera 1943). It is also considered as a promising path of reversing existing soil degradation, and meeting SDG (UN 2015) as long as soil biological processes are better understood (Lehman et al. 2015, 2020). The terms SQ and SH are often used interchangeably. However, SH emphasizes more on soil biological and biochemical processes and methods. Doran and Zeiss (2000) defined soil health as, “the capacity of a specific kind of soil to function, within natural or managed ecosystem boundaries, to sustain plant and animal productivity, maintain or enhance water and air quality and support human health and habitation”. Rinot et al. (2019) proposed to improve the SH methodology by combining the SH with the ecosystem services (ES) concept. Meanwhile, the European Commission has adopted the soil health terminology and will use it for achieving ambitious targets to improve soil’s performance by 2030 (Mission Board 2020). The main goal is to ensure >75% healthy soils, i.e. soils that are able to provide essential ecosystem services, in each EU member state. Their priority objective is reducing land degradation and restoring 50% of degraded land (Mission Board 2020).

1.3.2 Methods and Indicators of Soil Performance

Characteristic of indicators. Indicators are statistics or units related to changes in the quality or the condition of an object evaluated (Dumanski and Pieri 2000; Eurostat 2019). They provide simplified information, describe the state of specific phenomena and are useful for monitoring changes, providing an opportunity to compare trends and progress over a period of time. The main problem of selecting indicators is that one has to choose those that are suitable and representative for a certain condition, but at the same time, easy to understand and easy to measure on a regular basis (LADA 2013; Xie et al 2020). Soil quality indicators are based on and derived from soil parameters and indices. A soil parameter is a unit of primary information measured directly and quantitatively (i.e. dimensional), while a soil index is a unit of derivative information obtained via empirical models or mathematical calculations (mean, ratio, etc.) and it is non-dimensional (Enne and Zucca 2000). An indicator can be a parameter or index that provides brief and clear information about the condition or process to be assessed, measured and controlled in accordance with a specific goal. An indicator should contain quantitative information on how the processes evolve over time and vary in space, while selection of an optimal set of indicators should be reliable, environmentally and socially relevant, sensitive and cost-effective. An indicator should also be able to translate the present status of soils as well as predict trends of soil loss or change (Bünemann et al. 2018). The most important soil parameters/indicators are usually a subset of the palette of landscape indicators (Mirschel et al. 2020).

Soil state assessment. State indicators give a description of the quantity and quality of physical, chemical and biological phenomena (Smeets and Weterings 1999). Their measurement was normalized in many standards by ISO TC 190 "Soil Qualiy" and CEN/TC 444 "Test methods for environmental characterization of solid matrices" (CEN 2020). The use of these standards is essential for comparing soil data. Soil state assessment consisting of soil inventories in different time steps based on constant protocols is common in scientific-based monitoring of soil performance. Soil performance can be assessed by indicators comparing current soil conditions with established control points or baseline values (Snakin et al 1996; Boehn and Anderson 1997). Soil monitoring systems in many countries are based on such state assessment systems (Sychev et al. 2016; Glante et al. 2018; Gubler et al. 2018; Romanenkov et al. 2020). At local levels, participation of landowners, managers and other stakeholders in the development of monitoring systems of soil quality, including degradation aspects, has become an ethical standard over the past years (Schwilch et al. 2018) and is indispensable for achieving significant progress for keeping soil healthy (Bouma 2019b; Mission Board 2020). Indicators and assessment schemes have to be understandable at the field scale.

At a national scale, soil monitoring systems in many countries are implemented by different centres of competence, institutions and authorities and follow different concepts and methods. Yakovlev (2013) developed the principles of ecological regulation of soils, which consist in substantiating the criteria and levels of the permissible ecological state (quality) of soils and anthropogenic impact on them on the example of Russia. On the basis of these criteria and a five-level rating scale of the ecological state of the environment and the impact on the environment, he developed a system of consolidated indicators "state-impact" for soils, represented by uniform relative numerical values.

Although the data are potentially freely available, their practical availability for scientific evaluations and advice is severely restricted. Data collection, analysis, storage, administration and evaluation are usually separated in a disciplinary manner. For example, in Germany, widespread monitoring exists (Kaufmann-Boll et al. 2020) including about 800 soil long-term monitoring plots on cropland, grassland, forests, long-term field experiments as well as scientific studies on ecosystem monitoring, erosion monitoring, soil carbon and peat monitoring and other topics. There is a German database on soil biodiversity (Edaphobase) and an extended European version is under preparation, called EUdaphobase (Russel and Krogh 2020). Modern data repositories are under construction (Grosse et al. 2020). An international soil health database (SoilHealthDB, Jian et al. 2020) provides information about the magnitude and distribution of 42 soil health indicators and 46 background indicators for cropping regions of the globe, enabling definitions of thresholds and baselines. Rules for health and degradation assessments of grasslands and rangelands were developed by Herrick et al. (2019). There are (at least) two types of activity visible within the EU in the last few years.

- Implementation of EU-wide measurement schemes in order to collect data on the properties of European soils (see also CEN/TC 444), partly by financing respective projects, partly by collecting data in national databases and making them available in JRC databases. These data are then used to either describe the state-of-the-art or to predict further developments (e.g. including publishing these activities in order to prove that there is a need in the real world, e.g. Yigini and Panagos (2016)).
- Promoting soil issues have been neglected so far, not just in Europe but actually on a global scale. One example of this kind of activity is the publication of reports (e.g. Turbé et al. 2010) and even more attractive and highly successful in the form of atlases, e.g. for Europe (Jeffrey et al. 2010).

The US systems of soil quality and soil health assessments. Doran and Parkin (1994, 1996) developed soil state indicators of soil quality/health assessment for measuring and evaluating soil functions. These indicators needed to meet the criteria of reflecting ecosystem processes, include soil physical, chemical and biological properties and are sensitive to management and climate factors (Doran and Parkin 1996). On their basis, the Natural Resources Conservation Service of the United States Department of Agriculture developed, adopted and recommends tools and procedures for soil health and quality assessment, applicable to science and practice (USDA/NRCS 2020). Soil Quality Indicators are identified for characterising physical, chemical and biological soil properties (Table 1.2) that support potentially different functions. Practically, the productivity function is the focal aim and most common cause of application.

The Soil Management Assessment Framework (SMAF, Andrews et al. 2002) supports the selection of relevant soil functional and site-specific indicators and the computation of an overall soil quality (SQ) index based on dimensionless scoring functions from data of soil physical, chemical and biological indicator sets (Wienhold et al. 2009). SMAF was updated over recent years by including more chemical and biological parameters and was applied to other regions such as Southern Brazil or South Africa (Karlen et al. 2019; da Luz et al. 2019; Gura and Mnkeni 2019). The College of Agriculture & Life Sciences at Cornell University (New York, USA) has developed Comprehensive Assessment of Soil Health (CASH) protocols and offers analyses of CASH indicators and scientific advice in soil health assessment to farmers and other clients (Moebius-Clune et al. 2016; Soil Health Team 2020). A Soil Health Database has been developed for meta-analyses of soil health changes related to cropland conservation management (Jian et al. 2020).

Williams et al. (2020) applied the CASH methodology on 20 farms in south Sweden and found lower SH indexes of farm fields in comparison with unmanaged soil. Improved soil management through higher crop diversity, less mechanical soil disturbance and higher organic matter inputs improved soil health (Williams et al. 2020). This study confirmed the suitability of the mentioned SH state indicator methods for scientific studies.

Soil state indicator systems as shown in Table 1.2 and being part of the SMAF and CASH approaches are step forwards to recognizing the performance and deficiencies of soils. Evaluation scales and thresholds indicating whether soil is degraded are available for a few indicators, for example, pH and EC indicating acidification and sodification and salinization, respectively. Some more work is needed to develop the scales for the majority of other methods recommended here. Just biological properties and methods are partly very specific and have still unknown variability over space and time, requiring further studies (Wander et al. 2019). Also, it needs to be mentioned that methods developed by now are country specific and rarely comparable. Stronger efforts towards international studies for developing conversion rules and algorithms and international standards would be useful (Römbke et al. 2006, 2018; Höss and Römbke 2019; Jänsch et al. 2019; Thiele-Bruhn et al. 2020; Batjes et al. 2020).

Overall, the review shows that a comprehensive assessment of soil performance using the methodologies recommended by the USDA/NRCS is the domain of specialists. As some analyses are time-consuming, they require special laboratory analyses or can last some hours in the field (for example, steady-state field infiltration) to some weeks (for example, analyses of organic matter and carbon fractions) before reliable results for representative observation points will be available to clients. Also, field inspection and sampling are often decoupled from the analysis and assessment of data.

Field methods of assessing soil performance. Some scientists take the view that a single field inspection should provide a good estimate of soil quality/soil health. This view is related to the proven family doctor principle in human health care. The “soil doctor” must have good and comprehensive education, skills and experience, some modern fast-operating diagnostic equipment, and be well interlinked with acknowledged specialists and laboratories.

Examples of those field express methods are the SOILpak methods (McKenzie 1998, 2013), Visual Soil Assessment Method (VSA, Shepherd 2000, 2009) and the Muencheberg Soil Quality Rating (M-SQR, Mueller et al. 2012a, b, 2013,

Table 1.2 State indicators of soil quality/health recommended by the USDA (USDA/NRCS 2020)

Indicators are reflecting	Indicator	Remarks on methods
Physical properties	Aggregate stability	Field/lab, test kit
	Available water capacity	Special laboratory
	Bulk density	Cylindrical core method, laboratory
	Infiltration	Steady infiltration rate, field method
	Slaking	Slake test, field kit
	Soil crusts	Field method
	Soil structure and macropores	Descriptive field method
Chemical Properties	Reactive carbon	Laboratory, potassium permanganate oxidation method, also NRCS Active carbon field test kit
	Soil electrical conductivity	Measure of salinity, EC pocket metre
	Soil nitrate	Field test strip
	Soil pH	Portable pH pocket metre
Biological properties	Earthworms	Field methods (abundance, biomasss, diversity), but lack of other groups of soil invertebrates
	Particulate organic matter	Laboratory, time-consuming
	Potentially mineralizable nitrogen	Different special laboratory methods
	Soil enzymes	Different laboratory methods using biochemical assays
	Soil respiration	Different commercial field test kits available
	Total organic carbon	Special laboratory methods

2016). Indicators of visual recognizable soil structure like demonstrated in Fig. 1.8 are in the focus of these methods. Further soil structure assessment methods were developed and locally adapted (Murphy et al. 2013; Newell-Price et al. 2013; Pulido Moncada et al. 2014; Emmet-Booth et al. 2019). Development of these methods was inspired by the Visual Examination of Soil Structure (VESS) developed by Ball et al. (2007, 2017) and its preceding approaches. Methods are related to the productivity function of soil and are based on expert knowledge in terms of field manuals and simple field procedures of in situ measurement and evaluation (Mueller et al. 2014). Existing soil regular and thematic maps and data (status of nutrients, contaminants, crop yields, smart-farming maps, climate, cadastral data, etc.) should be used as basic and supporting information. This is important because climate factors in terms of temperature, precipitation and evapotranspiration determine the soil temperature and moisture regime of soils and thus the most important biophysical processes of plant growth and decay worldwide.

While SOILpak and VSA focus on dynamic aspects of soil quality in terms of soil structure parameters, M-SQR includes indicators reflecting both dynamic, soil inherent and climate parameters, thus enabling a functional fingerprint of soil's performance for cropping and grazing. Rating tables of M-SQR hazard indicators give information about soil states being considered as degraded. M-SQR also provides rating scores for the overall soil quality, which are correlated to crop yields both on regional and global scales (Smolentseva et al. 2014; Hennings et al. 2016; DWA 2018).

The soil testing method manual of the FAO (FAO 2020b) also orientates field methods for advising and educating farmers. Besides visual-tactile methods, vegetation analyses, simple devices of soil survey (Mueller et al. 2014) and field measurement kits (Table 1.2) serve as indicators of soil quality/health. Further field procedures for soil health assessment compatible with the SH assessment system of the USDA/NRCS (United States Department of Agriculture/Natural Resource Conservation Service) have been developed and tested (Thomsen et al. 2019). Those field methods of soil structure and/or overall soil quality are also the domain of experts. However, they enable participatory assessments of SQ/SH over some sampling points in quasi-real-time and provide ad-hoc results for all participating stakeholders.

SQ/SH assessment for more functions than soil productivity. To assess changes of soil at a complex level, e.g. as tools for decision making and considering causes of changes and consequences for the society, more comprehensive approaches for evaluating the multifunctional performance of soils are necessary. The DPSIR approach is a proven and popular indicator model for monitoring environmental processes in Europe at complex level, for example, for the Pan-European assessment and monitoring of soil erosion (Gobin et al. 2004). DPSIR is the abbreviation for **D**riving forces, **P**ressures, **S**tates, **I**mpacts and **R**esponses.

Soil functional indicators are important elements of Life Cycle Analysis (LCA) models (Roesch et al. 2019; Thoumazeau et al. 2019; Sonderegger et al. 2020). Soil databases and algorithms for a flexible mapping of purpose-targeted soil indicators have been developed (Panagos and van Liedekerke 2008; Makó et al. 2017).

Schulte et al. (2014) worked up a framework for managing soil-based ES for the sustainable intensification of agriculture which, besides productivity function, considered the functions of water purification, carbon sequestration, habitats for biodiversity and recycling external inputs. Similar ideas have already been proposed by Gardi et al. (2009) and were afterwards checked within the EU project EcoFINDERS, focusing both on the diversity of individual organism groups as well as specific ecosystem functions (Griffiths et al. 2016; Faber et al. 2020). The comprehensive approach of Schwilch et al (2018) includes definition and quantification of several provisioning, regulating and cultural ES from the natural capital of numerous locations characterized by soil threats. ES were used then as indicators for a state assessment and a 10-year scenario at field plot level.

Drobnik et al. (2018) developed an overall soil quality index for special planning by combining soil functions with ecosystem services. Van Leeuwen et al. 2019 created a decision expert model (DEX model) to quantify the capacity of a soil to supply the function of soil biodiversity and habitat provision (SB function). They defined a biodiversity function of soil and an indicator system based on soil attributes of nutrient status, biological status, structure and hydrological status. To develop decision tools for society, approaches and methods in SQ evaluation have been constantly updated.

Despite the progress made in the quantification of soil performance, there remain great knowledge gaps in understanding complex functional processes in soils, plant–soil-biota interactions and relationships between soil biodiversity and biogeochemical function across a range of ecosystems in particular (Jänsch et al. 2019; Wander et al. 2019; Chen et al. 2020).

1.4 Soil Degradation

1.4.1 Definitions and Concepts of Assessment and Monitoring

Essence and definition. The FAO defines soil degradation “as a change in the soil health status resulting in a diminished capacity of the

Fig. 1.8 Examples of visual-tactile methods of soil structure as semi-quantitative indicators of soil quality/health in the frame of existing evaluation schemes. **a** Favourable soil aggregates in a cropping systems, **b** unfavourable aggregates on same site, **c** soil slaking and crusting with implications for water and gas exchange between soil and atmosphere, **d** re-arrangement of aggregates after a drop-shatter test of the VSA procedure (Shepherd 2000), **e** favourable naturally crumbly structure of a Chernozem, **f** coarse columnar structure of a Solonetz. *Photos* L. Mueller

ecosystem to provide goods and services for its beneficiaries" (FAO 2020a, b). The terms "land degradation" and "soil degradation" are often used interchangeably as most authors agree that any degradation of soil is reflected in land degradation and often vice versa. Monitoring and assessing soil is, thus, a proper measure for sustainable development and achieving land degradation neutrality (Tóth et al. 2018). This is a challenging task as clear limits or thresholds identifying when soils or land are being degraded do not exist. From a local perspective, falling crop yields are seen as indicators of land degradation (Stocking and Murnaghan 2002). Soil and land degradation are the result of interactive processes of humans with nature. Multiple factors of soil, climate, land-use, economic dynamics and sociodemographic forces play a key role (Salvia et al. 2019).

Another term very closely related to soil and land degradation is desertification. Desertification is degradation of drylands (Dregne 1977), the worst case of soil degradation because it is very difficult to stop and to combat it. Desertification was defined by experts of the United Nations in 1977 as "the diminution or destruction of the biological potential of land" and can lead ultimately to desert-like conditions. It is an aspect of the widespread deterioration of ecosystems, and has diminished or destroyed the biological potential, i.e. plant and animal production, for multiple use purposes at a time when increased productivity is needed to support growing populations in quest of development" (UNEP 2020). The United Nations Convention to Combat Desertification (UNCCD 2012) defines desertification as "land degradation in arid, semi-arid and dry sub-humid areas resulting from various factors, including climatic variations and human activities". This process is interlinked with other threats to nature and society such as biodiversity loss and poverty, all strong obstacles to meet the sustainable development goals of the UN (IPBES 2018).

Disadvantage of the term "soil degradation". The use of the term "soil degradation" does not allow any clear interpretation. This arises from a disciplinary perspective and even from a sub-disciplinary perspective in soil science. In soil genetics, the term "degraded" is used when a soil type develops due to changing environmental conditions and management in the direction of another soil type. Degraded chernozems (leached chernozems), which develop from chernozems under more humid conditions, are known (Nikiforoff 1937). In this case, the term "degraded" has no functional meaning. Assessments can be even more contradictory if changes in soil properties due to use lead to changes in soil functions. It is more the rule than the exception, that one soil function is enhanced but another diminished. The productivity function and the biodiversity function mostly develop in opposite directions in the course of agricultural use. Then a disciplinary assessment decides whether the soil development is described as positive (aggraded) or negative (degraded). This discourse often arises in debates about the use-related change in hydromorphic soils with wet humus accumulation after drainage. Wetland conservationists refer to this development of peat soil as degradation, though crop-yield relevant soil parameters are not diminished (Schindler et al. 2003). Agriculturists value the improved productivity function of drained peat soils.

In the literature, there are many other definitions and concepts of soil and land degradation (Eswaran et al. 2001; IPCC SRCCL 2019). Some of them seem to be timeless and universal. However, all definitions need to be interpreted according to their purpose and temporal and local scale.

Attempts to quantify soil degradation. The GLASOD (Global Assessment of Soil Degradation) methodology was developed and coordinated about 30 years ago by the International Soil Reference and Information Centre, ISRIC, the Netherlands (Oldeman 1992), leading to global maps of about 1:10 million scale. This approach was based on existing soil and topographic maps and supplemented by expert-based regional and countrywide information. The underlying working definition of soil degradation (SD) was that "Soil degradation is defined as a process which lowers the current and/or future capacity of the soils to produce goods or services" (Oldeman 1992). Different types of degradation, the degree, the relative extent and causative factors of soil degradation were specified and delineated (Oldeman et al. 1990). Later, this methodology was refined and applied to specific regions (FAO 1994; Oldeman and van Lynden 1998). At this time, it remains the only basic and globally consistent information source on land degradation, which covers the whole area of the globe (Gibbs and Salmon 2015). GLASOD estimated 1216 million hectares worldwide while estimates of other scientists cover a huge range from about 470 to 6140 million hectares (Gibbs and Salmon 2015).

The GLASOD study and consecutive regional studies were intended as information for national action plans, including novel concepts in researching and monitoring soil changes, studying the driving forces and economic and social effects on local people and developing plans to halt degradation and desertification. Later studies utilized the great potential of enhanced and fast-developing remote-sensing methods and other geospatial technologies in combination with geographical information systems (Bai et al. 2008; Vågen et al. 2016; Dubovyk 2017; Dwivedi 2018; Panagos et al. 2020) and the open availability of high-resolution data and modelling tools (Eberle 2019; Giuliani et al. 2020).

Many regional and local experimental and modelling studies have been initiated to better understand the most relevant degradation and desertification processes at regional and local levels. Novel measurement systems were constructed, novel experimental setups generated, new data were obtained and understanding of the nature and magnitude of single degradation processes, as well as mitigation and combating strategies at farm and regional scales has increased were achieved. Examples are experimental and modelling studies of wind erosion (Funk et al. 2016; Zhu et al. 2020; Jarrah et al. 2020; Webb et al. 2020), water erosion (Chumbaev and Tanasienko 2016; Prasuhn 2020), soil compaction (Arvidsson and Keller 2007; Schjønning et al. 2016) and many others (Kosmas et al. 2014). In some EU countries, every single agricultural field has been classified regarding its risk of water and wind erosion (Steininger and Wurbs 2016). However, soil degradation state monitoring at the field level in the framework of soil quality/health assessment for soil functions does not yet exist.

1.4.2 Soil State Indication on Degradation and Desertification

Functional soil state indication on degradation, which is compatible with the soil quality/health concept as a basis for participatory decisions at regional and local levels, would be desirable. However, such concepts only exist to some extent (Virto et al. 2015).

Attempts to create a soil threat monitoring at EU level. A soil monitoring project for countries of the EU had been developed and tested 15 years ago in the framework of the ENVASSO project (Environmental Assessment of Soil for Monitoring) (Kibblewhite et al. 2008; Huber et al. 2008). It was an attempt to create a regular soil monitoring system, which provides reliable data at intervals of several years based on key indicators and harmonized national and regional approaches to measure and characterize soil degradation. The approach was based on the DPSIR concept, but the majority of indicators are state indicators. Tables 1.3, 1.4, 1.5 show the main threats identified and top three indicators selected by the international team of experts.

ER = Water, wind and tillage erosion, OM = Decline in Soil Organic Matter, SE = Soil sealing, land consumption and brownfield redevelopment, CP = Soil compaction and structural degradation, BI = Soil biodiversity, LS = Landslide activity, DE = Desertification. Dryness index = (annual precipitation)/(annual potential evapotranspiration), NA = not yet available, site-specific, CLC = Corine land cover, Calc = Calculation: average of 5 years out of the last 20 with the smallest area burnt annually (km^2), DM = Dry matter

Table 1.3 demonstrates that except for soil erosion, no clear baselines and thresholds in terms of absolute data could be quantified. For