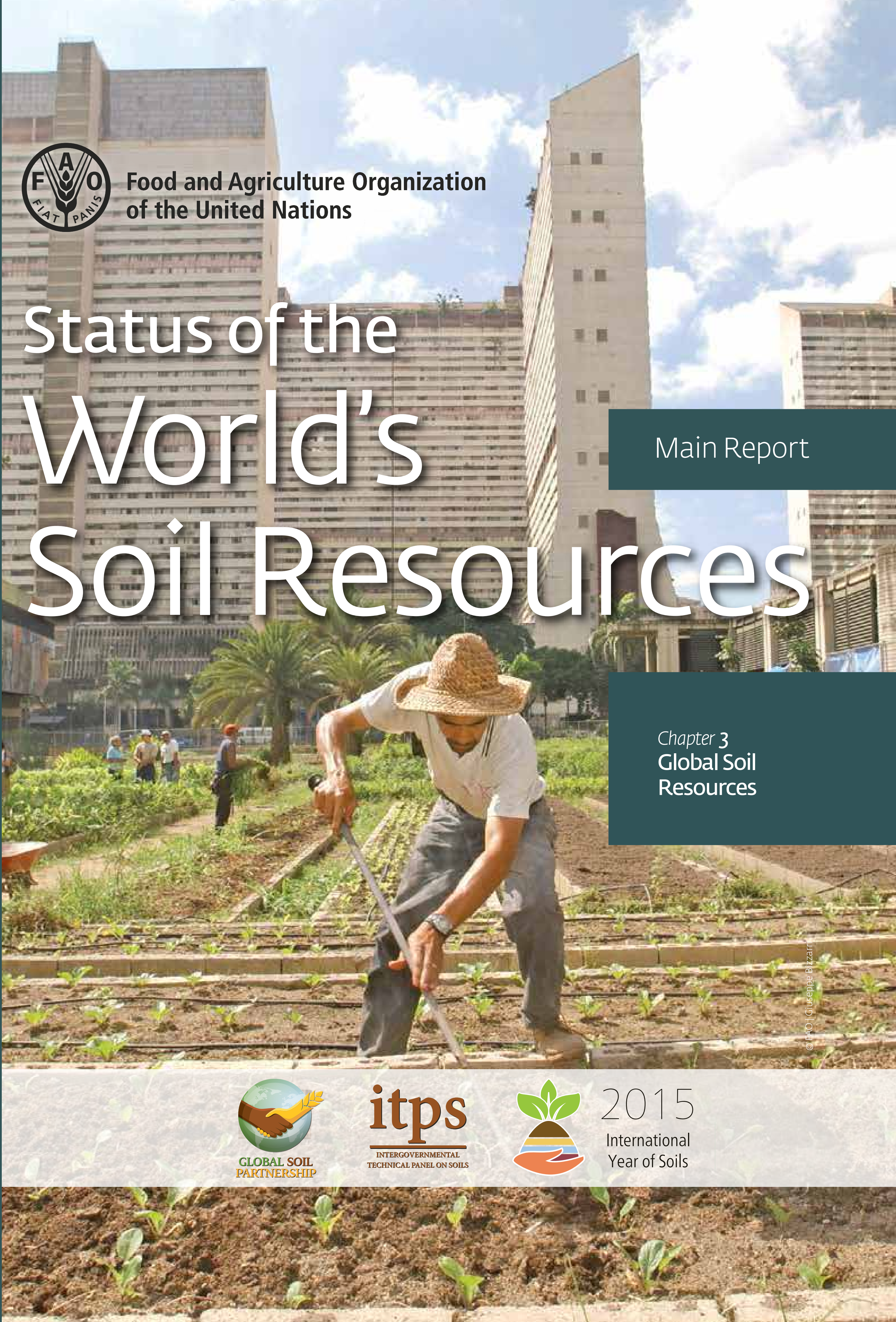
Food and Agriculture Organization
of the United Nations

Status of the World's Soil Resources

Main Report

Chapter 3
Global Soil Resources



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GLOBAL SOIL PARTNERSHIP

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INTERGOVERNMENTAL
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3 | Global Soil Resources

3.1 | The evolution of soil definitions

The definition of soil has changed over time. Early definitions (Kraut, 1853; Ramann, 1919) emphasized the geological or substrate aspect of soil as the upper weathering mantle of the earth's crust. At the end of the 19th century, Vasiliy Dokuchaiev formulated the paradigm of soil as a natural body formed by the combined effect of five soil-forming factors (climate, organisms, parent material, time and relief). This formulation effectively made Dokuchaiev the founder of a new science – pedology. His ideas were translated into English and promulgated by Coffey (1912) and Marbut (1921). Jenny (1941) published the equation of soil forming factors as independent variables; $S = f(cl, o, r, p, t\ldots)$. Dudal, Nachtergaele and Purnell (2002) added a human factor of soil formation, implying that soil is not exclusively a natural body.

For digital soil mapping, the soil forming factors were modified by McBratney, Mendonça-Santos and Minasny (2003) as $Sc = f(s, c, o, r, p, a, n\ldots)$ or $Sa = f(s, c, o, r, p, a, n\ldots)$ where Sc is soil classes, Sa is soil attributes, s is the soil or property at a point, and n is the spatial position. Grunwald, Thompson and Boettinger (2011) further expanded the factor model to the STEP-AWBH Model by including space and time to infer soil properties and their evolution in which the factors of human action, atmosphere, and water are added.

Defined in the simplest terms, soil is the upper layer of the Earth's crust transformed by weathering and physical/chemical and biological processes. It is composed of mineral particles, organic matter, water, air and living organisms organized in genetic soil horizons (ISO, 2013).

3.2 | Soil definitions in different soil classification systems

The World Reference Base for Soil Resources (FAO, 2014) classifies as soil any material within 2 m of the Earth's surface that is in contact with the atmosphere, but excluding living organisms, areas with continuous ice not covered by other material, and water bodies deeper than 2 m.

In the United States *Soil Taxonomy* (Soil Survey Staff, 1999) soil is considered to be a natural body comprised of solids (minerals and organic matter), liquid, and gases that occurs on the land surface, occupies space, and is characterized by one or both of the following: (I) horizons or layers that are distinguishable from the initial material as a result of additions, losses, transfers, and transformations of energy and matter; and (II) the ability to support rooted plants in a natural environment.

In the *Russian Classification System* (Shishov *et al.*, 2004), soil is defined as a solid-phase natural-historical body with a system of inter-related horizons composing a genetic profile and which derives from the transformation of the uppermost layer of the lithosphere by the integrity of soil-forming agents.

French pedologists put emphasis on the spatial aspects of soil as an 'objet naturel, continu et tridimensionnel' (a natural, continuous and three dimensional object) (AFES, 2008). A related variant considers that "soil in nature is a three-dimensional continuum, temporally dynamic and spatially anisotropic, both vertically and laterally" (Sposito and Reginato, 1992).

Urban soils including those 'sealed' by concrete or asphalt, strata of composts or other fertile materials applied to construct lawns and gardens, superficial layers, mine spoil or garbage heaps are also considered in some soil classification systems (Rossiter, 2007). The concept of soils as natural bodies also includes very thin films in caves or fine earth patches within desquamation cracks of hard rocks as found in Antarctic endolithic soils (Goryachkin *et al.*, 2012) and in underwater soils (Demas, 1993). Thus, the concept of soil becomes very broad. Soil scientists have even proposed to extrapolate it to other planets (Targulian *et al.*, 2010).

3.3 | Soils, landscapes and pedodiversity

The relationships between soils and landscapes were at the core of the 'zonality' concept developed by Dokuchaev and tested during his excursion to the Caucasus in 1898. He expressed the concept at the global scale in the form of many-coloured soil bands around the Earth. This zonal concept was also used in the United States 1938 classification of zonal, azonal, and intrazonal soils (Baldwin, Kellogg and Thorp, 1938). Along with zonal ideas, concepts of regularities in local soil patterns emerged. The earliest among these was the concept of soil series developed in the United States in 1903 (Simonson, 1952). The work of Neustuev (1931) on soil geography further developed the concept of regularities.

Another set of spatial soil patterns related to topography was recognized by Milne (1935) and Bushnell (1945) who proposed the term 'catena' (chain) and applied it to soil sequences on the slopes of mountains. Different soil catenas in landscapes all over the world were subsequently described and attempts were made to inventory them systematically (Sommer and Schlichting, 1997).

Fridland (1976) gave a new impulse to the theory of the 'soil/landscape' relationship by defining the types of soil systems related to landforms at different scales ('soil associations'). The relationships between soils – their ingredients, taxonomic distances, geometric shape and kinds of boundaries - were described and for some of them mathematic formulas were proposed.

Fridland's was the first attempt to analyse and quantify the pedological diversity of a territory. The concept of soil diversity, or pedodiversity (Ibáñez, Jiménez-Ballesta and García-Álvarez, 1990; Ibáñez *et al.*, 1995; McBratney, 1992), opened a new conceptual window in soil science (Ibañez and Bockheim, 2013; Toomanian and Esfandiarpoor, 2010). Approaches comprised the description and measurement of either the spatial distribution of soils, or their evolutionary stages by indicating rates of soil development. Soil development makes a contribution to the spatial heterogeneity of the soil because, together with other agents, soils with different evolutionary pathways participate in forming the soil cover and so contribute to the creation of specific soilscapes.

The term 'pedodiversity' and many tools for studying pedodiversity were adapted from biology. Pedodiversity, for example, can be measured just as biodiversity is measured - by means of special indices showing the abundance of species and the taxonomic distances between them. A set of mathematical methods, both parametric and non-parametrical, can be applied to quantify soil spatial heterogeneity.

The pedodiversity concept is an updated, quantification-oriented branch of soil geography. Its advantage is its compatibility with GIS and remote sensing technologies and its solid base in mathematics and statistics, which leads to a broad applicability in environmental sciences and biology.

3.4 | Properties of the soil

Because soils have physical, chemical, mineralogical, and biological characteristics, knowledge of the basic sciences of geology, chemistry, physics and biology contributes to understanding basic soil properties. The solid inorganic fraction defines the soil's *texture*, the amount of sand, silt, and clay. Solid particles are arranged into aggregates to form diverse structures by biological, chemical and physical processes. *Structure* describes the size, organization, and shape of the soil aggregates. *Consistence* and *strength* are how the soil deforms under pressure. Texture and structure influence *porosity* and *bulk density*. Gases or solutions occupy the soil pores. Soil reaction (pH), redox status, carbon, nutrients, and cation exchange capacity are key chemical properties. Secondary clay minerals e.g. smectite, vermiculite, illite, influence the soil physical and chemical properties and are the primary source of ionic exchange. The abiotic, inorganic properties create a platform for the biotic soil component.

Properties that are seen or felt are part of the soil morphology. Soil morphology is the object of study both in nature and in laboratories – micro morphology – with the help of microscopy and computer tomography. Soil colour is influenced by the content and type of organic matter and specific minerals including oxides (e.g. Fe oxi-hydroxides), and redox conditions. Horizon and total soil thickness describe internal organization and root and moisture availability.

3.5 | Global soil maps

Local soil investigations started at the end of the 19th century in Russia (see 3.3. above), but only after World War II were efforts geared towards more systematic national soil inventories. The first regional maps were produced in the early 1960s for Europe (FAO/UNESCO, 1962) and for Africa (D'Hoore, 1964).

The development of a global soil map was initiated by the International Soil Science Society in 1960 and implemented by FAO and UNESCO between 1971 and 1980, resulting in the FAO-UNESCO Soil Map of the World.[1]

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[1] A digital version of this map is downloadable at: http://www.fao.org/geonetwork/srv/en/resources.get?id=14116&fname=DSMW.zip&access=private

This *Soil Map of the World* was, from 1995 onwards, systematically updated under the Soil and Terrain Database (SOTER) program carried out by FAO, ISRIC and UNEP together with national soil survey services. This resulted in several regional updates, including for Latin America and the Caribbean, large parts of Africa, and Eastern and Central Europe. In parallel, other organizations, notably the Joint Research Centre (JRC) of the European Commision (EC) and the USDA, undertook regional soil updates, while several countries completed national soil inventories and maps (China, Brazil, Botswana and Kenya etc.). This updated information was harmonized with the digitalized Soil Map of the World and published by a consortium of FAO, IIASA, JRC, ISRIC and CAS in 2006 as the *Harmonized World Soil Database* (HWSD). Although not fully harmonized and consistent, the HWSD contains the most up-to-date and comprehensive soil information that is currently available. The latest version of this database, giving geo-referenced estimates of twenty soil characteristics, is available online.[2]

In 2006, work began on the design and planning for a soil grid of the world at fine resolution (100 m) and this became known as GlobalSoilMap. The intent was to integrate the best available data from local and national sources and deliver the information online. The format and resolution was to be compatible with other fundamental data sets on terrestrial systems (e.g. vegetation, land cover, terrain, remote sensing). The initial focus was Africa (Sanchez *et al.*, 2009) and this led to the establishment of the African Soil Information System (AfSIS).[3] The technical and logistical complexity of the project has been substantial but good progress has been made during the initial research phase of the project and continental coverages are starting to be published.[4] A full summary is provided by Arrouays *et al.* (2014).

Another, more recent initiative that arose from the GlobalSoilMap effort is Soil Grid 1km[5] which is a collection of updatable soil property and class maps of the world at a relatively coarse resolution of 1 km. These maps are being produced using state-of-the-art model-based statistical methods: 3D regression with splines for continuous soil properties and multinomial logistic regression for soil classes. SoilGrids 1km are outputs of a system for automated global soil mapping developed within the Global Soil Information Facilities framework. This system is intended to facilitate global soil data initiatives and to serve as a bridge between global and local soil mapping (Hengl *et al.*, 2014).

Information on the availability of global, regional and national soil maps has been summarized by Omuto, Nachtergaele and Vargas (2012). The plan for developing the global soil information system was endorsed by the Plenary Assembly of the Global Soil Partnership in July 2014 and it is now being implemented.[6]

A simplified global soil map with the major soil groups is given in Figure A 35 (Annex).

3.6 | Soil qualities essential for the provision of ecosystem services

Soil functions depend on a number of physical, chemical and biological soil properties that in combination determine essential soil qualities. These qualities in turn guarantee that the soil can fulfil its ecological and productive services. Soils differ considerably in terms of properties, qualities, limitations and potential. Significant changes may occur over very short distances, making environmental and soil monitoring difficult (Brammer and Nachtergaele, 2015).

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[2] http://www.fao.org/soils-portal/soil-survey/soil-maps-and-databases/harmonized-world-soil-database-v12/it/

[3] http://www.africasoils.net

[4] http://www.clw.csiro.au/aclep/soilandlandscapegrid/

[5] http://www.isric.org/content/soilgrids

[6] http://www.fao.org/fileadmin/user_upload/GSP/docs/plenary_assembly_II/pillar4.pdf

Soil management has a considerable effect on how the soil may fulfil its ecosystem services. Mineral and organic fertilizer may compensate for poor inherent nutrient conditions in a soil; drainage may remedy excessive wetness in soils, or leach salts when these are present; amendments (lime or gypsum) may correct very acid or highly sodic soils. However, these interventions always have a cost in terms of labour and inputs, and they may also have negative side effects, such as groundwater contamination.

In this section a number of soil qualities essential for the provision of ecosystem services are discussed and related to the major soil groups summarized and illustrated in Annex A35.

3.6.1 | Inherent soil fertility

The capability of a soil to provide sufficient nutrients to crops, grasses and trees is a major quality of soils that supports all provisioning services of the ecosystem. Sixteen nutrients are essential for plant growth and living organisms in the soil. These fall into two different categories: *macronutrients* and *micronutrients*. Macronutrients are the most important nutrients for plant development and relatively high quantities are required. Macronutrients include: carbon (C), oxygen (O), hydrogen (H), nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), and sulphur (S). Micronutrients, on the other hand, are needed in smaller amounts, but are still crucial for plant development and growth. Micronutrients include iron (Fe), zinc (Zn), manganese (Mn), boron (B), copper (Cu), molybdenum (Mo) and chlorine (Cl). Nearly all plant nutrients are taken up in ionic forms from the soil solution as cations or as anions.

Soil properties directly related to the amount and availability of nutrients in the soil are: (I) *soil texture* (clayey soils contain more nutrients than sandy ones); (II) the type of *clay minerals* present (smectitic clays absorb more ions than kaolinitic ones); (III) the *soil organic carbon content* (more SOC corresponds with a larger amount of nutrients); and (IV) the *cation exchange capacity* that corresponds to the total of Ca, Mg, K, Na (basic ions) and Al and H (acidic ions) exchangeable with the soil solution. A large amount of available nutrients is present in Vertisols, Chernozems (Borolls), Kastanozems (Ustolls) and Phaeozems (Udolls). Also volcanic soils (Andosols) and alluvial soils (Fluvisols/Fluvents) generally have a large nutrient content. On the other hand, sandy soils (Arenosols/Psamments) and highly leached soils (Ferralsols/Oxisols and Acrisols/Ultisols) generally have a small nutrient content.

The amount of nutrients that a soil can provide to plants within the growing season represents a limit to nutrient mining. Nutrient mining occurs when crops take out a high proportion of the nutrients available in the soil, leaving a nutrient imbalance that threatens the sustained provision of food and ecosystem services. These challenges are discussed in Section 6.8. Figure 3.1 illustrates an estimation of the nutrient availability in soils globally based on information contained in HWSD.

Soil depth to a hard or an impermeable layer is a vital factor that determines the capability of roots to take hold and determines the total volume of nutrients and water available to crops and vegetation. Soils tend to be deeper when strong weathering conditions prevail over a long period and wherever the parent material is readily weathered. Typical soils include Ferralsols and Nitisols). Shallow soils often occur in mountainous areas (Leptosols) and in dry areas characterized by indurated layers of silica, calcium carbonate or gypsum (Durisols/Durids, Calcisols/Calcids and Gypsisols/Gypsids). Each plant type has its own ideal rooting conditions. Tubers are the most sensitive to soil depth and volume limitations (Fischer *et al.*, 2008; Grossnickle, 2005; Unger and Kaspar, 1994; McSweeney and Jansen, 1984; Myers *et al.*, 2007). Figure 3.2 illustrates global soil rooting conditions

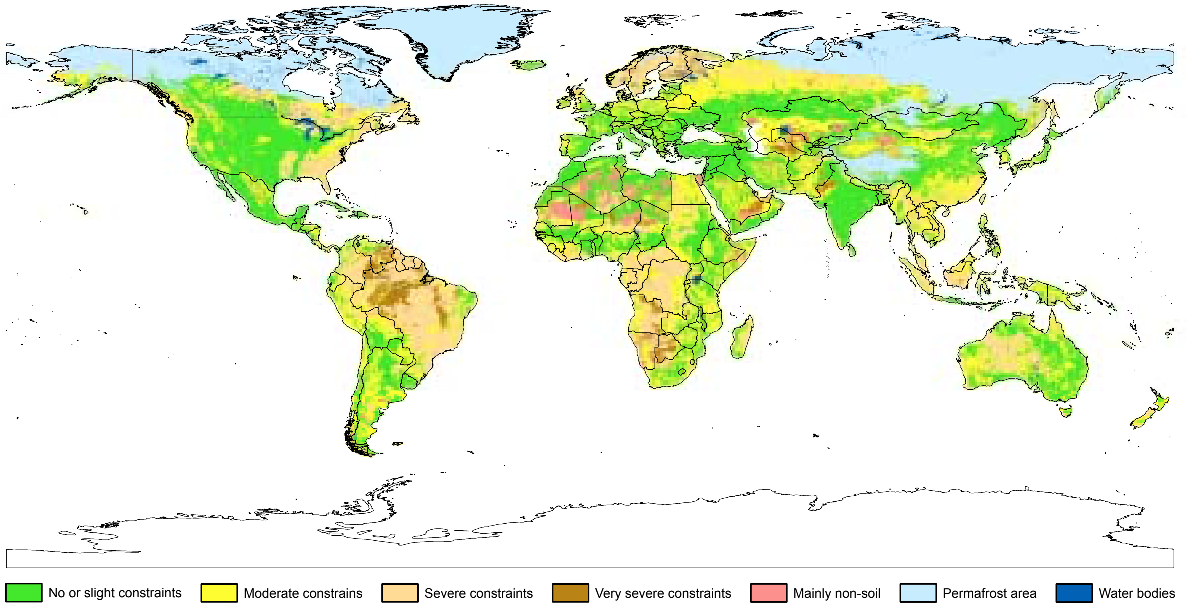


Figure 3.1 | Nutrient availability in soils. Source: Fischer et al., 2008.

The soil pH is a measure of its hydrogen ion concentration and indicates the acidity or alkalinity of the soil. Optimum availability of nutrients occurs around pH=6.5. Toxic concentrations of H and Al occur when the pH drops below 5.5. Values of pH above 7.2 indicate an alkaline reaction and may be symptomatic for the immobilization of nutrients. Very high pH values over 8.5 result in the dispersion of the soil particles and a collapse of structure. High rainfall results in more acid soils (Ferralsols/Oxisols, Alisols, Plinthisols, Acrisols/Ultisols, Podzols/Spodosols), while drier conditions often lead to the accumulation of Gypsum (Gypsisols/Gyspsids) or other less soluble salts (Silicon and Calcium Carbonate) in Durisols/Durids and Calcisols/Calcids. The soil pH is also important to the characterization of soil threats to ecosystem services such as acidification (section 6.4) and sodification (Section 6.5). A global map of soil pH is given in Section 6.4.

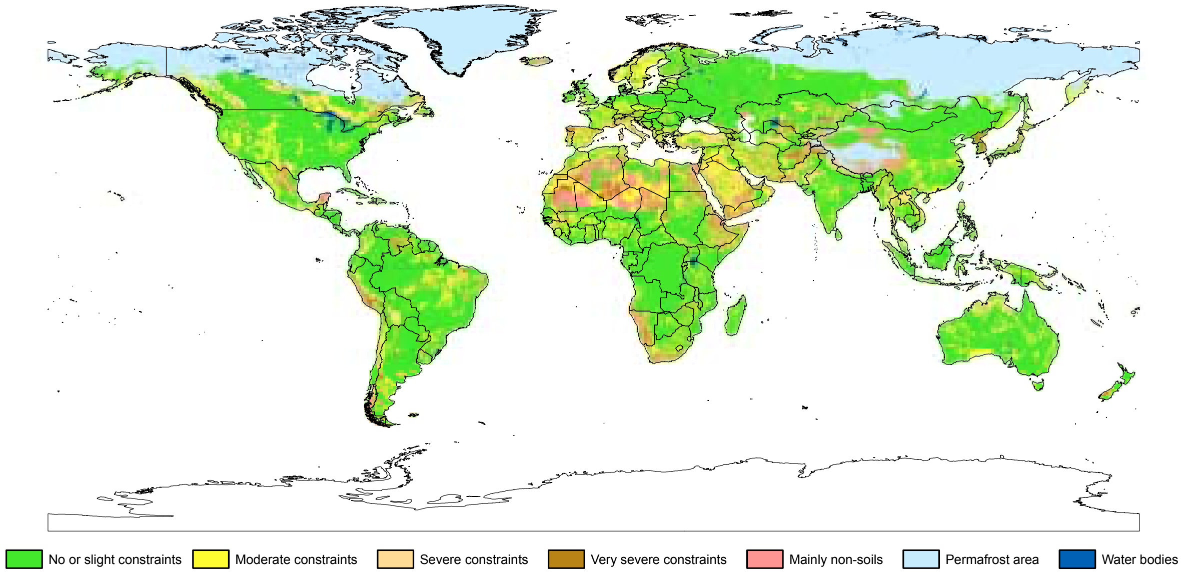


Figure 3.2 | Global soil rooting conditions.
Source: Fischer et al., 2008.

Accumulation of water soluble salts: soils in relatively dry areas are often characterized by the accumulation of water-soluble salts (NaCl, Na_2SO_4, etc.) and of less water-soluble salts ($CaCO_3$, $CaSO_4$). These salts may form indurated layers that limit the soil depth available for roots. This accumulation is often a natural process resulting in soils such as Solonchaks/Salids, Calcisols/Calcids, Gypsisols/Gypsids, Durisols/Durids. In irrigation schemes, which are most commonly developed in dry areas, the problem may be human-induced and made worse by the use of saline irrigation water, by insufficient leaching/drainage, or by the conversion to irrigation of soils formed from marine sediments. Most salt-affected soils have moderate to severe limitations for crop production. Section 6.5 deals specifically with salinization and sodification problems.

Toxic elements and other soil fertility problems: some toxic elements such as aluminium occur naturally in acid soils. The parent material may also be a natural source of undesirable elements (for instance cadmium) that may be a problem for human and animal health. Some soils have a high phosphorus adsorption ratio (Andosols and Nitisols/Kandi subgroups) that make P fertilization cumbersome. Atmospheric deposition of toxic elements may also contaminate soils as discussed in section 4.4.

3.6.2 | Soil moisture qualities and limitations

The moisture stored in or flowing through the soil affects **soil formation**, its **structure** and **stability**, and **erosion** run-off. Soil moisture is of primary concern with respect to plant growth. The depth of the groundwater table and the availability of **oxygen** in the soil also affect soil ecosystem functions. The physical properties of soils (texture, structure, porosity, drainage class, permeability) are of prime importance in this respect.

The capacity to store water and moisture in a soil is largely determined by its texture, structure, organic carbon content and depth. Soil moisture provides a buffer for crops during dry periods and is a built-in safeguard against run-off and erosion. Ecological functions of this parameter are discussed in Chapter 7. High soil moisture capacities are typical for deep clayey soils, rich in organic matter and containing modest amounts of $CaCO_3$ (Chernozems, Cambisols). The lowest soil moisture capacities are encountered in sandy soils (Arenosols) or very shallow soils (Leptosols). Very high soil moisture storage occurs in volcanic soils (Andosols) and in many peat soils (Histosols). Figure 3.3 illustrates the distribution of different soil moisture storage classes globally.

Oxygen availability is a critical factor for plant growth. Inadequate oxygen supply to the roots leads to the formation of an underdeveloped root system which is not able to provide sufficient nutrients and water to the plant. Oxygen availability is basically defined by drainage characteristics of soils related to soil type, soil texture, soil phases and terrain slope, all of which play an important role in determining the proportion of gases and water into the soil. Soil phases define specific soil and terrain characteristics. Gleysols/Aquic suborders, Stagnosols and Plinthosols often suffer from temporary saturation with groundwater or rain water, resulting in poor oxygen availability for part of the year. Oxygen availability can be improved by farming practices (e.g. adapted tillage) and by farming inputs such as artificial drainage (Crawford, 1992; Erikson, 1982; Fischer *et al.*, 2008).

3.6.3 | Soils properties and climate change

Soils are both affected by and contribute to climate change. The carbon that is fixed by plants is transferred to the soil via dead plant matter including dead roots and leaves. This dead organic matter creates a substrate which soil micro-organisms respire back to the atmosphere as carbon dioxide or methane depending on the availability of oxygen in the soil. Some of the carbon compounds are easily digested and respired by the microbes, resulting in a relatively short residence time. Others become chemically and/or physically stabilised in soils and have longer residence times (as described in Chapter 2). Soil organic carbon can also be thermally decomposed during fire events and returned to the atmosphere as carbon dioxide. Remaining charred material can persist in soils for long periods (Lehmann *et al.*, 2015).

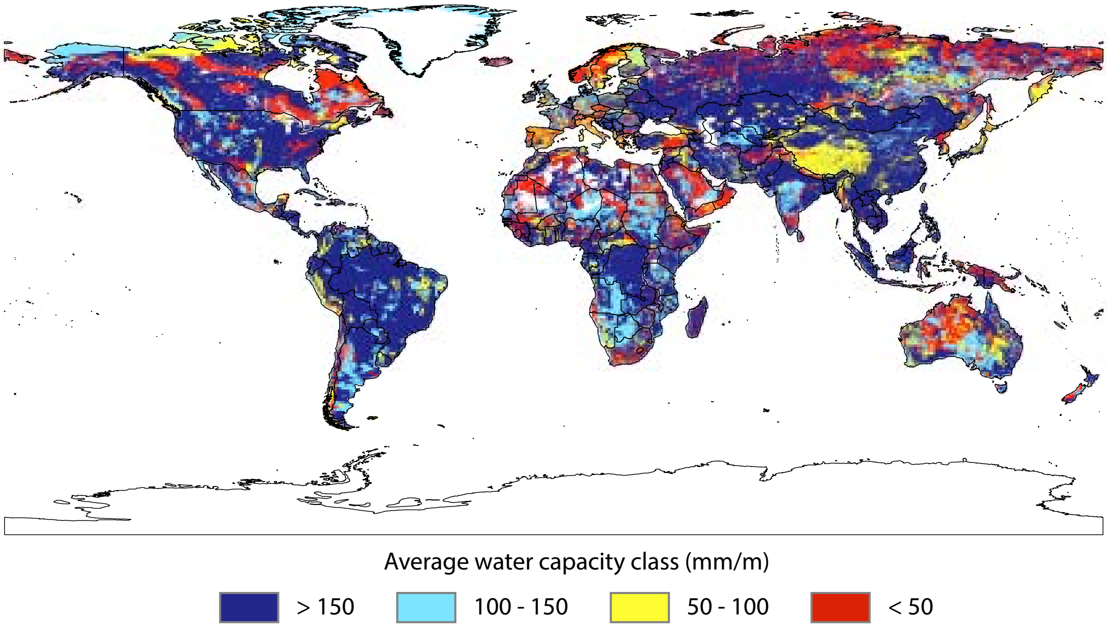


Figure 3.3 | Soil Moisture storage capacity.
Source: Van Engelen, 2012.

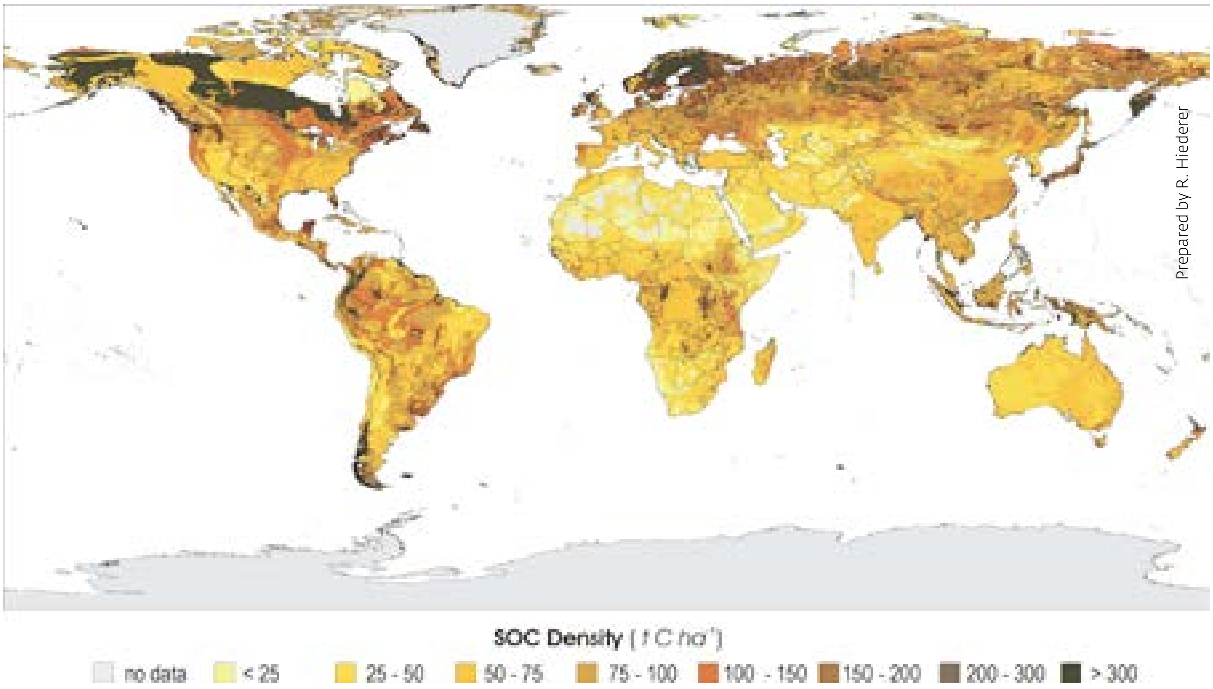
Soil organic carbon improves the physical and chemical properties of the soil by increasing the cation exchange capacity and the water-holding capacity. It also contributes to the structural stability of soils by helping to bind particles into aggregates. Soil organic matter (SOM), of which carbon is a major part, holds a great proportion of nutrients, including trace elements, which are of importance to plant growth. SOM mitigates nutrient leaching and contributes to soil pH-buffering capacity. It is widely accepted that the organic matter content of the soil is a major factor contributing to soil functions, including that of organic C storage, which has important feedbacks with the Earth's climate system (Chapter 2).

A large organic carbon content is found in peat soils (Histosols/Histisols), in volcanic soils (Andosols/Andisols) and in steppe soils (Chernozem/Borolls, Kastanozems/Ustolls and Phaeozems/Udolls). Large organic carbon contents are not always indicative of fertile soils because carbon may also accumulate under wet and cold conditions as in Podzols/Spodosols and Cryosols/Gelisols, and in some hydromorphic soils such as Gleysols. Changes in SOC represent one of the major soil threats – see the discussion in section 6.2. The global distribution of soil organic carbon is given in Figure 3.4.

Crysols/Gelisols are soils which are frozen for a large part of the year. In taiga areas they often occur together with Histosols. Global warming in these areas will have a significant effect by allowing agriculture to move more northwards. However, mineralization of organic carbon may be accelerated, with negative consequences for GHG release.

3.6.4 | Soil erodibility and water erosion

The susceptibility of a soil to water erosion is primarily determined by the erosive potential of the rainfall, the slope of the land surface and position of the soil in the catchment, and the vegetative cover on the soil surface. Soil erodibility refers to the susceptibility of soil to erosion by water and is an important secondary control on the intensity of water erosion. Most clay-rich soils (e.g. Vertisols with the exception of erodible self-mulching forms) have a high resilience because they are resistant to detachment. Coarse textured, sandy soils (e.g. Arenosols/Psamments) are also resilient because of low runoff even though these soils are easily detached. Medium textured soils, such as silt loam soils are only moderately resistant to erosion because they are moderately susceptible to detachment and they produce moderate runoff. Soils having a high silt content are the most erodible of all soils. They are easily detached, tend to crust and produce high rates of runoff. Organic matter reduces erodibility because it reduces the susceptibility of the soil to detachment, and increases infiltration, which reduces runoff and thus erosion. Soil structure affects both susceptibility to detachment and infiltration. Permeability of the soil profile affects erodibility because it affects runoff. Past management or misuse of a soil (e.g. by intensive cropping) can increase a soil's erodibility, for example if the subsoil is exposed or if the organic matter has been depleted, or where the soil's structure has been destroyed or soil compaction has reduced permeability. Section 6.1 discusses soil erosion by water in more detail. Soil erodibility worldwide, as characterized by the k factor in the RUSLE equation, is represented in Figure 3.5.



Prepared by R. Hiederer

Figure 3.4 | Soil Organic Carbon pool (tonnes C ha^{-1}).

3.6.5 | Soil workability

Soil workability refers to the ease of tillage, which depends on the soil's interrelated characteristics of texture, structure, organic matter content, etc., on the soil's gravel content, and on the presence of continuous hard rock at shallow depth. Depending on the soil characteristics, soil workability also varies with the soil moisture content. Some soils are easy to work regardless of the moisture content, but other soils – such as Vertisols - can be worked only at a specific moisture status. This is true especially for farming systems employing manual cultivation methods or using only light machinery. Soil workability is also related to the type of soil management adopted. While low and intermediate input farming systems mainly face constraints related to soil texture and soil structure, high-level input mechanized farming systems mainly face constraints related to irregular soil depth and stony and rocky soil conditions. Indeed, the use of heavy field equipment is not possible on stony soils or on soils characterized by irregular soil depth. This factor can prevent soil degradation, for example by compaction (Earl, 1997; Fischer *et al.*, 2008; Müller *et al.*, 2011; Rounsevell, 1993). Figure 3.6 shows the distribution of the constraints to soil management and food production due to soil workability worldwide.

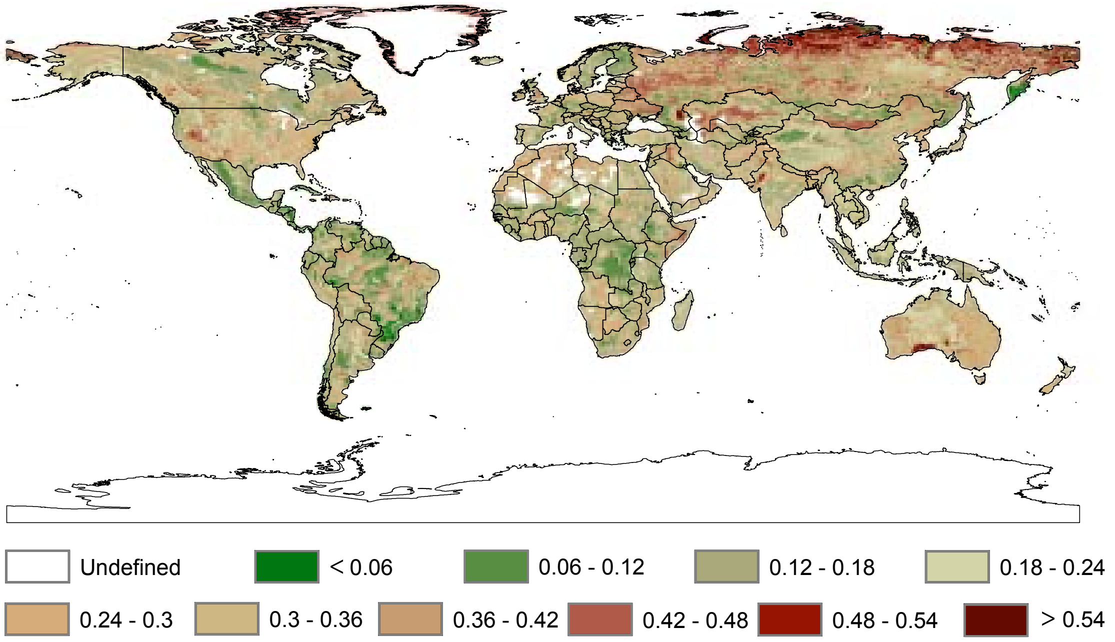


Figure 3.5 | Soil erodibility as characterized by the k factor.
Source: Nachtergaele and Petri, 2011.

3.6.6 | Soils and ecosystem goods and services

Figure 3.7 illustrates the suitability of soils for supporting crops. The evaluation is based on soil health but excludes climatic considerations (except for low temperatures). In Table 3.1, the contribution of the main soil types to major ecosystem services (food security, climate regulation, water regulation and socio-cultural provisions) is estimated at a scale from zero to five. The ratings are based on soil characteristics and quality as measured by: suitability for growing crops; organic carbon content; water holding capacity; and capacity to support infrastructure and store archaeological remains.

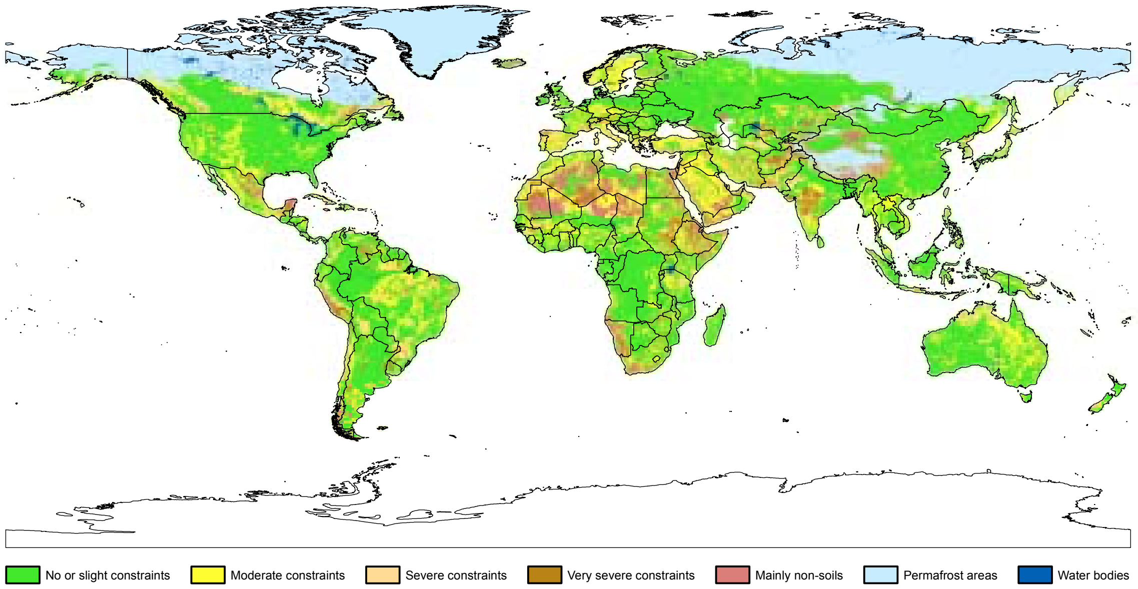


Figure 3.6 | Soil workability derived from HWSD.
Source: Fischer et al., 2008.

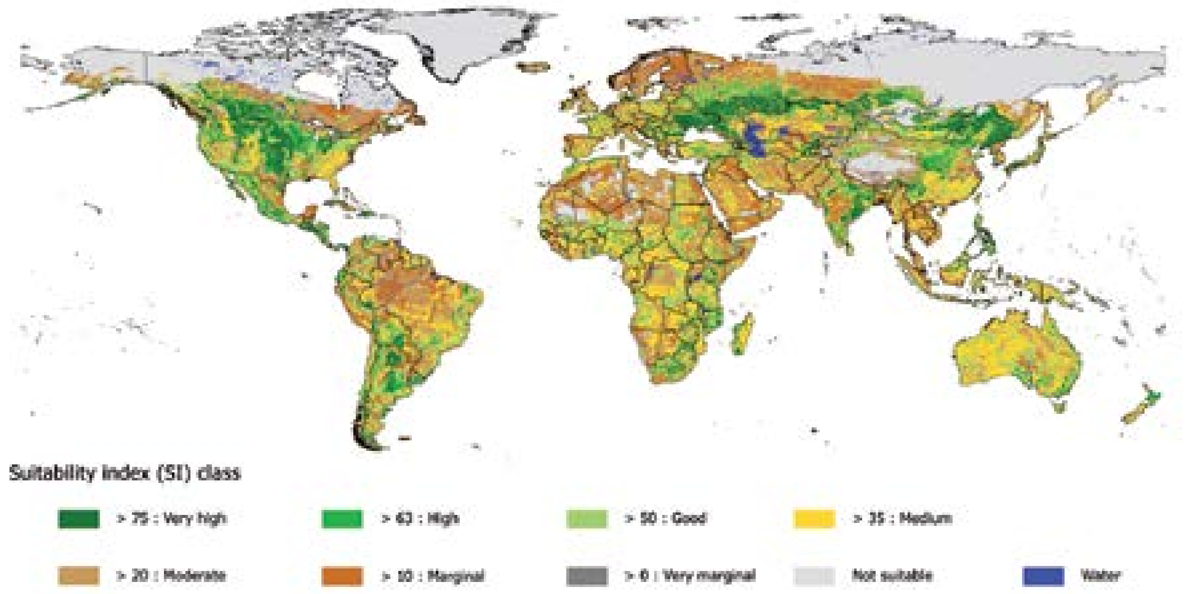


Figure 3.7 | Soil suitability for cropping at low input, based on the global agro-ecological zones study.
Source: Fischer et al., 2008.

Table 3.1 | Generalized ecosystem service rating of specific soil groups (WRB) [7]

	Ecosystem Services					
Reference Soil Groups	Food	Climate	Water	Cultural	SUM	Major Service
Histosols	2	5	5	3	15	Climate Change
Anthrosols	5	5	5	4	19	Food Security
Technosols	1	3	2	4	10	Infrastructure
Cryosols	0	5	2	3	10	Climate Change
Leptosols	1	1	2	1	5	Water runoff
Vertisols	4	2	3	1	10	Food Security
Solonetz	1	1	1	1	4	Very few
Solonchaks	1	1	1	1	4	Very few
Podzols	1	3	1	1	6	Biomass
Ferralsols	2	4	3	1	10	Biomass
Nitisols	4	3	4	1	12	Food Security
Plinthosols	2	1	2	1	6	Biomass
Planosols	1	1	1	1	4	Very few
Gleysols	2	1	3	1	7	Food Security
Stagnosols	2	1	3	1	7	Water storage
Andosols	4	3	5	1	13	Food Security
Chernozems	5	4	4	1	14	Food Security
Kastanozems	3	4	2	1	10	Food Security
Phaeozems	4	4	3	1	12	Food Security
Umbrisols	3	3	3	1	10	Water runoff
Durisols	1	1	1	1	4	Very few
Calcisols	1	1	2	1	5	Very few
Gypsisols	1	1	1	1	4	Very few
Retisols	2	1	2	1	6	Biomass
Acrisols	2	1	2	1	6	Food Security
Lixisols	2	1	2	1	6	Food Security
Alisols	1	1	2	1	5	Biomass
Luvisols	3	2	2	1	8	Food Security
Cambisols	3	2	3	1	9	Food Security
Regosols	2	1	1	1	5	Biomass
Arenosols	1	1	1	1	4	Biomass
Fluvisols	4	2	4	2	12	Food security
Wassents	0	2	2	1	5	Very few

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[7] Soil Taxonomy equivalents given in the Annex, except for Wassents that are a suborder in Soil Taxonomy

3.7 | Global assessments of soil change - a history

Global assessments of soil and land degradation started more than 40 years ago, but have until now not achieved a clear answer on where soil degradation takes place, what impact it has on the population, and what the cost to governments and land users would be if the decline in soil, water and vegetation resources continued unabated. Although institutional, socio-economic and biophysical causes of soil degradation have been identified locally in many case studies, these have seldom been inventoried systematically at national or regional level. Much of the investment in land reclamation and rehabilitation during recent years has been driven by donor interest to fund action, rather than research to understand the scope of the problem. Even knowledge about what works and what does not work in combating soil degradation is scanty, and there has been little systematic investigation. In recent years, however, the World Overview of Conservation Approaches and Technologies (WOCAT) consortium has begun to make a substantial contribution through its systematic collection of information on sustainable soil and water conservation practices and their impacts.

The first comprehensive assessment of global soil degradation was based on expert opinion only. This was the *GLobal Assessment of human-induced SOil Degradation* - GLASOD, published by UNEP/ISRIC (Oldeman, Hakkeling and Sombroek, 1991). *The Land Degradation Assessment in Drylands* project (LADA) was launched by GEF, implemented by UNEP and executed by FAO between 2006 and 2011 in support of the UNCCD. LADA developed an approach based on remotely-sensed NDVI data (the *Global Land Degradation Assessment* – GLADA). The project also used an ecosystems approach that brought together and interpreted information from pre-existing and newly developed global databases to inform decision makers on all aspects of land degradation at a global scale (GLADIS: the *Global LAnd Degradation Information System*).

During this period other important and broader environmental assessments took place, notably the *Millennium Ecosystem Assessment* (MA, 2005) and the periodical review of the *State of the Environment* by UNEP with the GEO- reports (UNEP, 2012). FAO published a *State of Land and Water* (SOLAW) in 2011. The Economics of Land Degradation (ELD) initiative (ELD, 2015) provided in 2015 a first estimate of the cost of land degradation at global scale based on rather scattered and uncertain information. The annual economic losses due to deforestation and land degradation were estimated at EUR 1.5–3.4 trillion in 2008, equaling 3.3–7.5 percent of the global GDP in 2008. All of these studies used the results of one of the three global inventories: GLASOD, GLADA or GLADIS which are discussed in more detail below.

3.7.1 | GLASOD: expert opinion

An expert consultation on soil degradation convened by FAO and UNEP in Rome in 1974 recommended that a global assessment be made of actual and potential soil degradation. This assessment, which was conducted in collaboration with UNESCO, WMO and ISSS, was based on the compilation of existing data and the interpretation of environmental factors influencing the extent and intensity of soil degradation. The assessment considered such environmental factors as climate, vegetation, soil characteristics, soil management, topography and type of land utilization. The results of this assessment were compiled as a world map of soil degradation. During the next four years FAO, UNESCO and UNEP developed a provisional methodology for soil degradation assessment and prepared a first approximation study identifying areas of potential degradation hazard for soil erosion by wind and water, salinization and sodification. Maps at a scale of 1:5 M covering Africa north of the equator and the Middle East were prepared (FAO/UNEP/UNESCO, 1979). These first efforts were then scaled up into the Global Assessment of Human Induced Soil Degradation Project or GLASOD. The project was initiated by UNEP. It had a duration of 28 months and was executed by ISRIC. In order to cover the whole world, 21 regions and individual countries were defined and experts on these regions were asked to prepare detailed maps of soil degradation. More than 250 soil scientists and environmentalists cooperated in this project (Oldeman, Hakkeling and Sombroek, 1991). The global results of the GLASOD project are available online.[8]

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[8] http://www.isric.org/UK/About+ISRIC/Projects/Track+Record/GLASOD.htm

A regional follow-up in Southeast Asia resulted in a more detailed database for that region: ASSOD (Van Lynden and Oldeman, 1997).

Since its publication, some expert opinion has faulted GLASOD, questioning the objectivity and reproducibility of an assessment based on expert opinion as an assessment approach (Sonneveld and Dent, 2007). However, at the time GLASOD was developed there were few alternatives available, especially given the overall lack of remotely sensed data at the time. Even today the criticism seems unwarranted as remotely sensed techniques and most modelling approaches have so far failed to come up with more useful assessments. GLASOD results are presented in Figure 3.8.

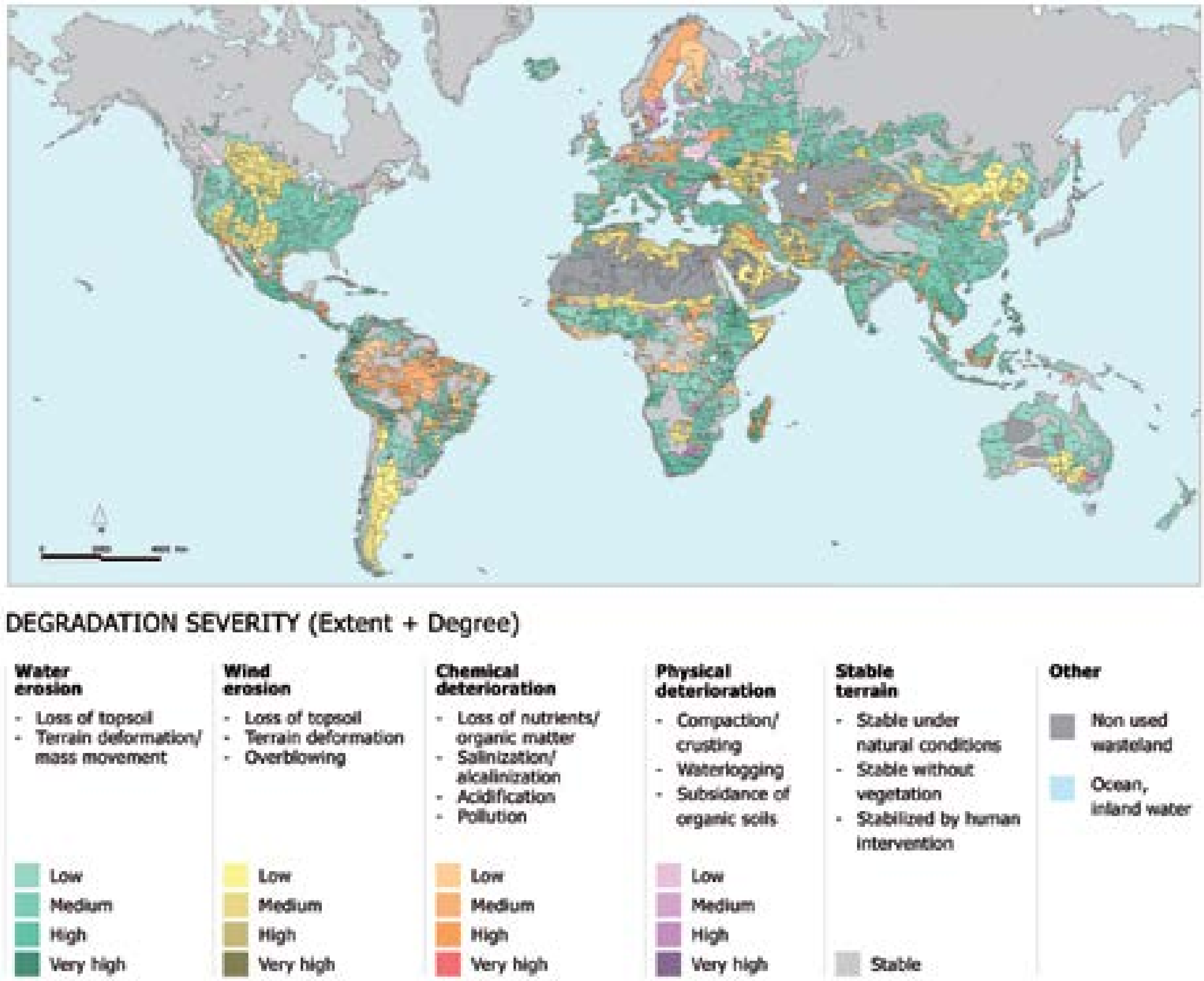


Figure 3.8 | GLASOD results.
Source: Oldeman, Hakkeling and Sombroek, 1991.

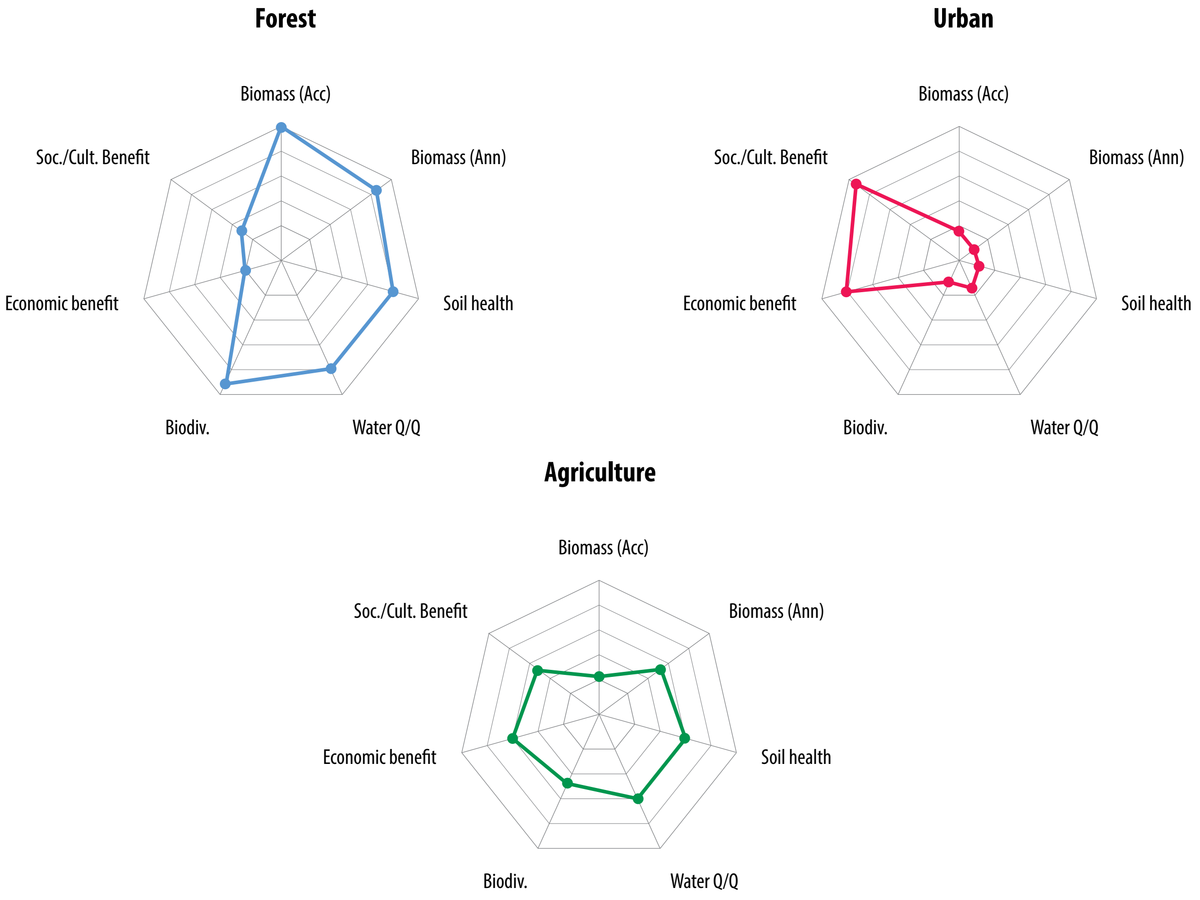
3.7.2 | LADA-GLADIS: the ecosystem approach

The first approaches of LADA (see 3.7 above) used remotely-sensed NDVI data to prepare the *Global Land Degradation Assessment* – GLADA (Bai *et al.*, 2008). However, this was soon superseded by a complementary approach that focused on the actual status and trends of land resources in terms of six factors: biomass, water resources, soil health[9], above-ground biodiversity, and economic and social provisions that contribute to ecosystem goods and services (Figure 3.9). The evaluation was based on interpretation of global databases available in the public domain, using documented algorithms to achieve a rating for each of the six factors in terms of status and trends. In order to map the various aspects, a special 'global land use system' was developed (Nachtergaele and Petri, 2011) which allowed cause and effect to be linked. Results were presented in radar diagrams (Figure 3.10) that showed the variability of ecosystem services provided as a function of land use and the need for trade-offs between different factors related to ecosystem goods and services. The GLADIS system is accessible on-line at:

http://www.fao.org/nr/lada/index.php?option=com_content&view=article&id=161&Itemid=113&lang=en

An example of an output for global soil compaction is shown in Figure 3.10.

Criticism of the GLADIS system focused on the unreliability of some of the global databases used and on questions about the downscaling relationships that were developed at local scale (such as the RUSLE). For the specific factor - soil health - the absence of an assessment of wind erosion is certainly a limitation, while the fact that no difference is made between 'natural' and 'human induced' soil erosion is also confusing. These weaknesses have been recognized and should be corrected where possible during the further development of the GLADIS information system which is pending.



Forest

Urban

Agriculture

Figure 3.9 | Example of the effect of land use on indicative factors for ecosystem goods and services

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[9] The soil health status was obtained by comparing the soil suitability for the actual land use. The soil health trend was based on a combination of ratings for the risk of erosion by water, the soil compaction risk, a nutrient balance, and the soil contamination and soil salinization risks.

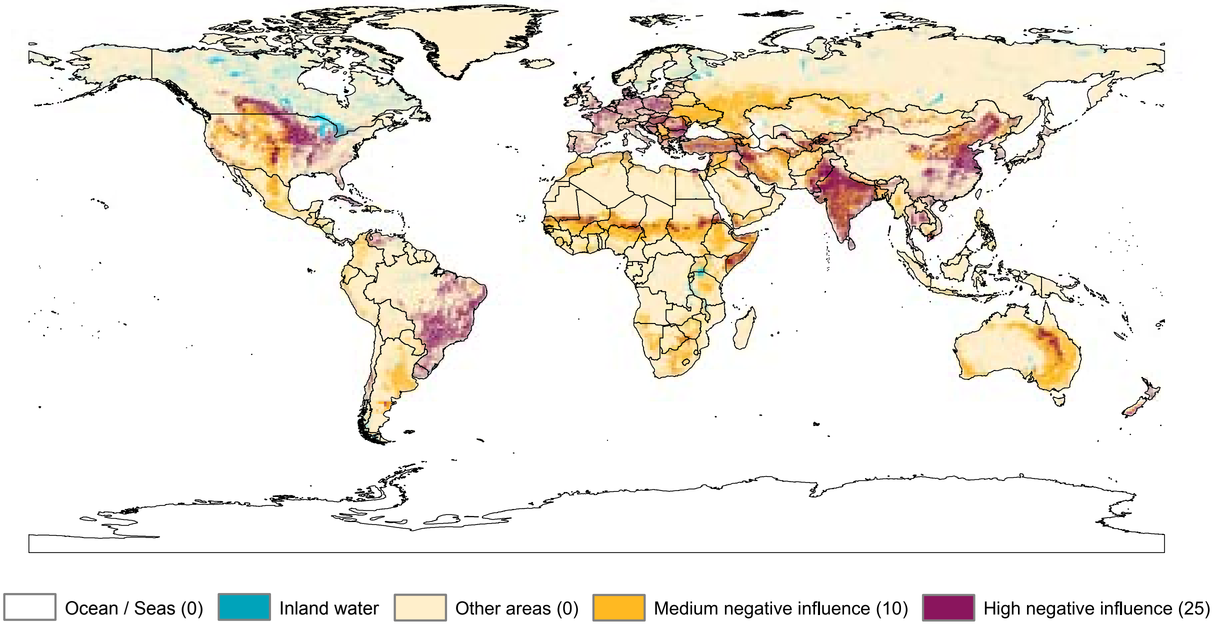

Figure 3.10 | Soil compaction risk derived from intensity of tractor use in crop land and from livestock density in grasslands.
Source: Nachtergaele et al., 2011

3.7.3 | Status of the World's Soil Resources

The present book – *The Status of the World's Soil Resources* - takes a different approach from the ones described above by focusing on well documented and peer reviewed research data on soil degradation processes, status and trends in scientific literature at all levels. It also draws attention to the uncertainty of estimates made.

The quantity and quality of information on soil degradation is shown to be very variable in different regions. Some regional statements - Africa, Eurasia, Near East, Latin America - still rely on GLASOD or ASSOD. For other regions, such as North America, no regional harmonized approach has been undertaken. Only the EU and the South West Pacific have made progress in establishing new regional updated approaches.

The report also shows the great differences that exist in data and data availability on soil resources and soil change information at national level. Systematic sampling/surveying and monitoring does take place for selected major land uses (forests, arable lands) in most EU countries, the United States and Canada, China, Australia and New Zealand. However, results are not always made available in the public domain. The progress in digital soil mapping may help more countries to produce harmonized data and to make the information public.

The data presented in this book constitute a baseline inventorying the documented knowledge at a point in time: 2015. Future progress can thus be measured against this baseline.

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