1

The State and Future of Soils

1.1. Soils as a key component of the critical zone

1.1.1. *Definitions*

The critical zone extends from the lower atmosphere to unweathered rocks [NAT 01, LIN 10]. It therefore includes vegetation, fauna, soils and water tables. Without it, humanity could not survive, hence the term critical [LIN 10, NAT 01].

According to the Larousse dictionary, *soil* is the surface layer of crust of a telluric planet (like Earth and Mars). In French, the term “soil” and/or “ground” also has many other meanings such as “surface”, “ground staff”[1], etc. The plural of the term, “soils”, is often preferred by soil specialists to emphasize the diversity of soil natures and properties that constitute a continuum referred to as “soil cover”.

1.1.2. *Soil functions and services*

The first book in this series, named *Soils as a Key Component of the Critical Zone 1: Functions and Services*, deals with the functions and services of soils. The functions relate to ecosystems, and the services relate to humanity. However, this distinction is questionable since ecosystem functions, for the most part, are also services. Conversely, the priority given to a single service (intensive agricultural production, for example) may

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Chapter written by Christian VALENTIN.

[1] See Chapter 1 of *Soils as a Key Component of the Critical Zone 1: Functions and Services*.

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affect certain functions (water purification, for example). In 2015[2], as part of the International Year of Soils, the FAO drew up a list of eleven functions and services:

– regulation of biogeochemical cycles (C, N, O, Al, Si, P, S, Mn, Fe, Cu, etc.) and nutrient cycling[3];

– carbon sequestration[4];

– climate regulation (see the volume *Soils as a Key Component of the Critical Zone 1: Functions and Services*);

– regulation of the water cycle[5] and flood regulations;

– water purification[6] and soil contaminant reduction;

– habitat for soil organisms[7], some of which can be pathogenic such as the soil bacillus *Burkholderia pseudomallei*, which is responsible for melioidosis, an often-fatal disease [MAN 17];

– provision of food, fiber and fuel[8];

– source of pharmaceutical and genetic resources [BER 06, NES 15];

– foundation for human infrastructures[9];

– provision of construction materials[10];

– cultural heritage[11], particularly in terms of archaeological archives.

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[2] Available at http://www.fao.org/resources/infographics/infographics-details/en/c/284478/.

[3] See Chapter 3 of *Soils as a Key Component of the Critical Zone 1: Functions and Services.*

[4] See the books *Soils as a Key Component of the Critical Zone 1: Functions and Services* and *Soils as a Key Component of the Critical Zone 6: Ecology.*

[5] See Chapter 2 of this volume, and Chapter 3 of *Soils as a Key Component of the Critical Zone 1: Functions and Services* and *Soils as a Key Component of the Critical Zone 3: Soils and Water Circulation.*

[6] See Chapters 7–9 of this volume, and *Soils as a Key Component of the Critical Zone 4: Soils and Water Quality.*

[7] See the book *Soils as a Key Component of the Critical Zone 6: Ecology.*

[8] See Chapters 5–7 of *Soils as a Key Component of the Critical Zone 1: Functions and Services.*

[9] See Chapter 8 of this volume and Chapter 9 of *Soils as a Key Component of the Critical Zone 1: Functions and Services.*

[10] See Chapter 9 of *Soils as a Key Component of the Critical Zone 1: Functions and Services.*

[11] See Chapter 11 of *Soils as a Key Component of the Critical Zone 1: Functions and Services.*

This list is far from comprehensive, as soil renders many other services. For example, it is also involved in air quality (see Chapter 3 of this volume). For tens of thousands of years, it has offered mankind a place of burial, constituted an element of myths and entered into rites[12].

1.1.3. *Soil and land degradation, desertification*

Soil degradation is defined as a change in the soil's state that results in a decrease in its ability to provide goods and services[13]. The FAO refers to soil health, a term that reflects an anthropomorphic view. If soil is a living environment, soil cover is not an individual who could be "sick" or "dying", given that it is an evolving continuum. In contrast, soil can indeed undergo degradation; its soft horizons can even disappear under the effect of erosion. It seems more correct, and indeed more frequent, to refer to soil quality. Moreover, even artificialized soil can provide services, as shown in Chapter 8 of this volume. As a result, deeply transformed soil, such as urban soil, may not be considered "very degraded" if it has been able to sufficiently maintain or restore several important properties (bacterial and mesofaunal activities, enzymes, sufficient porosity for infiltration, nutrients, etc.) that are likely to provide ecosystem services.

Land degradation covers a broader concept, but is also more fuzzy, since this term refers to both the solid part of the Earth's surface (as opposed to liquid surfaces) and the soil or all of the resources in the critical zone.

Desertification is the process of land degradation in arid and semiarid areas. It is also a term used for other climatic zones if they undergo irreversible change of the land to such a state that it can no longer be recovered for its original use.

1.2. The difficult assessment of the state and kinetics of soil degradation or enhancement

While it has become relatively easy to globally monitor atmospheric parameters such as air temperature or CO_2 content, or even to characterize soils [EHL 14] and gullies [HAR 15] on Mars, no global system has yet really been put in place to determine and monitor the state of soil degradation. One of the difficulties comes from the very definition of soil degradation, which is tainted

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[12] See Chapter 10 of *Soils as a Key Component of the Critical Zone 1: Functions and Services.*

[13] Available at www.fao.org/soils-portal/soil-degradation-restoration/fr/.

with a certain relativity, since it refers to goods and services whose expectations vary according to populations and eras. Furthermore, it is difficult to rely on a baseline: what soil has never been subjected to a degradation agent (fires, acid rain[14], radionuclide fallout[15] such as ^{137}C)? Moreover, the many forms of degradation prohibit any use of a single, universal indicator of degradation that would simply have to be monitored periodically, as is the case, for example, for the CO_2 content in the atmosphere. Can we be satisfied with only taking the sealed surfaces by constructions and infrastructures into account and, therefore, only basing our land degradation assessment on urban sprawl[16], or surfaces that are so eroded[17] that no agricultural, pastoral or forest production is possible anymore, or even on surfaces abandoned by agriculture [FIE 08]?

In addition to this essentially spatial approach, often linked to the assessment of areas considered to be "arable", there is a more qualitative approach to soil properties or "quality" in terms of permeability (Chapter 2 of this volume), biological and chemical fertility (Chapter 9), pH (Chapter 4), salt content (Chapter 5) and biological and chemical contaminants (Chapters 6 and 7).

1.2.1. *Global assessment*

Despite these difficulties, three types of approaches have been adopted in order to assess the degree and extent of soil degradation on a global scale.

1.2.1.1. *Expert assessment*

The first attempt, coordinated by United Nations Environment Program (UNEP; Global Assessment of Soil Degradation [GLASOD] [OLD 90]), was based on expert assessment from all countries. This approach has the advantage of field knowledge – something that is too often lacking in spatial remote sensing and modeling approaches. Moreover, it is the data from this international effort that continue to be referred to due to lack of a more recent practice of the same type. However, such an approach is not without its flaws. It stumbled on the issue of the standardization of criteria and the homogenization of assessments. The other difficulty arises from the hidden agendas of some countries that have declared their soils to be fully degraded, probably in the hope

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[14] See Chapter 4.

[15] See Chapter 3.

[16] See Chapter 8.

[17] See Chapter 8.

of increasing a better share of international aid, while it is evident that some of their soils under forests are not degraded or only lightly degraded, particularly in protected areas.

1.2.1.2. *Satellite-derived primary productivity*

Another approach (The FAO Global Assessment of Land Degradation and Improvement, GLADA, [BAI 08]) was aimed more at assessing land degradation than soil degradation. It is based on primary production, estimated from the Normalized Difference Vegetation Index (NDVI) and calculated from satellite data. This quantified objective index can be obtained regularly across the globe. However, this is more of a vegetation cover assessment than a soil degradation status assessment. Although lack of cover does promote erosion processes, not all vegetation cover has the same soil conservation suitability, and some tree plantations may even be related to severe erosion (see Chapter 3).

1.2.1.3. *Modeling*

Combining these spatial remote sensing data with databases and different models, the FAO followed an even broader approach (Global Land Degradation Information System) [NAC 10], combining vegetation, soil, water and human pressures. It has thus drawn up several maps of the state of soil degradation and trends. Despite their undeniable value, these maps have several inherent flaws regarding the unequal quality of the data, the models used and the lack of confrontation with the ground truth. These are closer to risk maps than to actual degradation maps.

1.2.1.4. *Uncertainties that are still too great*

Depending on the approach adopted, the global estimate of the total degraded area thus varies from 1 to more than 6 billion hectares [GIB 15], which is a difference of more than 50 million km^2. There is therefore a significant risk of overestimating available land, particularly for non-food agricultural uses (biofuels, green chemistry). Moreover, these approaches do not all agree on the geographical distribution of degraded land, which raises the issue of the location of priority efforts to be made in terms of soil protection or rehabilitation.

1.2.2. *Forms of degradation*

Among the ten major types of soil degradation, it is classic to distinguish those of a biological, physical and chemical nature, a classification which is a little too academic given that these degradations are linked, one (the reduction of organic matter content, for example) often leading to others (surface crusting, erosion, compaction, nutrient depletion):

– reduction of soil biodiversity: several chapters in this volume (including Chapter 7) and *Soils as a Key Component of the Critical Zone 6: Ecology* address this critical issue for ecosystem services;

– reduction of organic matter content: similarly, most chapters in this volume address this issue; organic carbon content largely determines the main functions of soils. In addition, organic matter, for example, is one of the components, along with clays, that can erode most easily;

– soil sealing by surface crusting (Chapter 2) or by urban sprawling (Chapter 8), which would consume about 20 million hectares of agricultural soil per year in the world [FAO 15];

– erosion (Chapter 3), which would be responsible for the loss of more than 3 tons of soil per inhabitant and per year [FAO 15];

– compaction : trampling by humans or livestock [HIE 99], and the passage of heavy machinery over wet soils (fields, pastures or forests) lead to a reduction in structural porosity[18] (inter-aggregates) under wet conditions, with numerous consequences [NAW 13] such as a reduction in infiltrability (Chapter 2). This increases the risk of runoff. In addition, rut formations can channel runoff and encourage the appearance of rills and gullies (Chapter 3). By increasing soil resistance to penetration, compaction reduces the possibility of seed development and rooting. Decreased oxygen, water and nutrient supplies to plants cause reductions in plant growth and yields. Compaction also has negative effects on microbial and enzymatic activities, as well as on soil biodiversity. By promoting anoxic (anaerobic) conditions, compaction increases the risk of methane emissions. Furthermore, the addition of nitrogen fertilizers in wet conditions and soil compaction results in an increase in nitrous oxide (N_2O) emissions. Methane and nitrous oxide are greenhouse gases that have a much higher effect than those of CO_2: the global warming potential of nitrous oxide is 298 times higher than that of carbon dioxide, and 25 times higher than that of methane. Compaction is measured by the increase in apparent density (a compacted horizon has a higher apparent density than before its compaction) and the resistance to penetration by penetrometers. For a more

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[18] See [BRA 16].

detailed study of the causes and effects of tillage, it is useful, even essential, to characterize a tillage soil profile [ROG 04] by opening a pit perpendicular to the direction of tillage. It is then appropriate to delimit volumes according to their bulk density, their resistance to penetration and rooting, by connecting them to the various cultural operations (depth and, if possible, dates and water conditions). Particular attention must be paid to the discontinuities of rooting depending on the presence of a plough pan. About 4% of the emerged lands, i.e. 68 million hectares, would be compacted [FAO 15], of which almost half (33 million hectares) would be in Europe. Overgrazing, and therefore the carrying capacity exceedance, would be responsible for one-sixth (16%) of the world's soil compaction. In order to limit compaction, it is necessary to avoid the use of heavy machinery on wet soils. Soils that are rich in organic matter are more resistant to compaction. The fact remains that forest soils, although rich in organic matter, can also suffer degradation by compaction under the pressure of heavy machinery used for logging. Very compacted soils can see their porosity and their possibility of rooting improved by subsoiling, especially when localized [HAR 08]. Some plants (e.g. *Stylosanthes hamata*) also tend to improve the physical conditions of the soil [LES 04];

– waterlogging: like compaction, the replacement of air by water in soil porosity has many biological consequences. Most terrestrial organisms cannot withstand the lack of oxygen [PAR 08]. Excess water also causes physical (such as slumping) and chemical degradation (N_2O emission) [FAO 15]. Soil hydromorphy can have direct anthropogenic causes such as the lack of drainage in irrigation systems, industrial or urban sites, and during the constructions of dams or hillside reservoirs. During the GLASOD assessment, waterlogging due to irrigation without adequate drainage was reportedly underestimated by half in the Indo-Gangetic plains and Pakistan. By the reduction of pumping into the water tables through deep roots and evapotranspiration, deforestation of the upper slopes also tends to raise water tables and thus clog the soil in the lower parts [HAM 12]. Although it is responsible for greenhouse gas emissions (NH_4, N_2O), the voluntary hydromorphic nature of flooded paddy fields is not considered a form of soil degradation. There are also indirect anthropogenic causes of waterlogging, such as those related to global warming. Rising sea levels raises the hydrological base level so well that hydromorphy gains ground over considerable surface areas. Melting glaciers and permafrost are also causing soil waterlogging, particularly in Canada and Siberia. Moreover, it is in Russia that the waterlogged soils cover the largest areas with 360 million hectares, or 21% of the total surface area and 10% of cultivated lands. In coastal areas, these processes are clearly amplified by the subsidence of deltas (Bangladesh, Thailand, Vietnam, etc.), due to excessive pumping in water tables, and by the slightest sediment inflow due to the multiplication of upstream dams (see Chapter 3). The delta of the Chao Phraya river that irrigates Bangkok would thus sink by 5–15 cm per year [SYV 09], and that of Niger would sink by 2.5–12.5 cm per year. In the latter case, oil extraction is the main source of this subsidence. Waterlogging problems are often accompanied by soil salinization and sodization problems (Chapter 5). These three processes would be responsible for a loss of 30–35% of the soil productivity concerned [FAO 15];

– nutrient imbalance: in the absence of fallow periods, or of sufficient replenishments in the form of organic manure (Chapter 9) or fertilizers of agricultural or industrial origin to compensate for export through crops and erosion (Chapter 3), the soil becomes imbalanced in terms of nutrients. This process is particularly sensitive for phosphorus in Africa and Southeast Asia [WHO 10]. In Africa, only three countries have a zero or positive balance [FAO 15];

– acidification (Chapter 4) leading to reduced yields, particularly in Australia, South-East Asia, and sub-Saharan regions [FAO 15];

– salinization (Chapter 5) often linked to irrigation without drainage in arid and semi-arid countries (see waterlogging); 20% of irrigated soils, or 62 million hectares, have already been affected [QAD 14];

– metallic (Chapter 6) and organic (Chapter 7) pollution with its consequences on biodiversity and human (and animal) health.

1.2.3. *Main factors of soil degradation*

The various chapters of this volume present the anthropogenic factors of soil degradation that, to a large extent, are linked to the expansion of cultivated areas and the intensification of agriculture. The extension is particularly sensitive in Africa, where the curve follows that of the population. Intensification has resulted in a massive use of synthetic fertilizers and pesticides, a geographical separation between cereal-growing and livestock-growing regions, an increase in the size of plots, the removal of hedges, the use of increasingly heavy agricultural or forestry machinery, a large extension of irrigated areas, etc.

This pressure on agricultural land has increased, particularly after the 2008 food crisis, by the process of land grabbing[19], which can be defined as the acquisition (long-term lease, often 30–99 years, concession, purchase, etc.) by private or state funds ("sovereign wealth funds" of vast cultivable areas larger than 10,000 ha in a foreign country – most often in Africa) to produce food, but more frequently, biofuels. However, competition for the same commodity (corn, for example) between a food and energy use ("first generation" biofuels) weighs on the world rates of these commodities, and makes them less accessible to the poor. It has been well established that the sharp increase in the use of U.S. corn for ethanol production, which was linked to financial incentives, is at the root of the food crisis that began in 2007, and the hunger riots in several countries in 2008. This gave rise to the "food versus fuel" controversy. An important issue to be added to this one is the interest of biofuels in terms of greenhouse gas reduction [EUR 11, SEA 08]. Indeed, a life-cycle assessment, including nitrous oxide emissions and taking changes in land use (for example the replacement of a primary forest in Indonesia by a palm oil plantation) into account, tends to show that the balance of greenhouse gas emissions is most often negative (corn for ethanol in the United States, palm oil in Indonesia). The most favorable situation would be that of ethanol production from sugar cane in Brazil.

In addition to agricultural, pastoral and forestry production (food, fibers, wood, latex, etc.), biofuels (ethanol and oils) are increasingly being produced as well as other bio-based molecules for chemical (e.g. biopolymers) and pharmaceutical industries.

However, these are not the only pressures on soils, as they are also subject to destruction and threats from mining, urban sprawl (Chapter 8) and the rise in sea level. This can not only have effects on coastal erosion and soil waterlogging, but also on the salinization of vast areas by saline intrusion of the continental water tables.

1.2.4. *What's the trend: degradation spiral or U-curve?*

According to the latest data published by the FAO [FAO 15], the soil situation would only be improving on 10% of the earth's surface. In contrast, 25% would still be suffering very severe degradation, 8% moderate degradation and only 26% slight or no degradation. The remainder would be divided

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[19] See Chapter 2 of *Soils as a Key Component of the Critical Zone 2: Societal Issues.*

between 18% of bare soil and 2% of aquatic surfaces. If we only consider 22% of the land area that has agricultural potential, 60% would already be affected by various forms of soil degradation. The current general trend would therefore be negative. Many studies, at least local and national, show that the situation has particularly worsened since the motorization and intensification of agriculture.

This rather gloomy picture is consistent with the pessimistic predictions of Thomas Malthus (1766–1834) who, in 1799, in *An Essay on the Principle of Population, as it Affects the Future Improvement of Society with Remarks on the Speculations of Mr. Godwin, M. Condorcet, and Other Writers*, notably responded to the optimistic *Esquisse d'un tableau historique des progrès de l'esprit humain* published in 1795 shortly after the death of its author, Nicolas de Condorcet (1743–1794). This pessimistic vision of the future of our planet's natural resources, and therefore of the soil, has been updated many times [EHR 68, MEA 72]. According to this current stream of thought, technological development obeys the law of diminishing returns: innovations are becoming increasingly difficult and costly for ever smaller gains. This would bring humanity closer to the point where non-renewable resources (such as soil on a human scale, see Chapter 3) are exhausted. As long as there is no regulation of common goods, they will be doomed to degradation. This is the "tragedy of the commons" [HAR 68]. The process of degradation of natural resources would conform to a downward spiral [SCH 00]: users (farmers, pastoralists, etc.) would become poorer as the resources they exploit decrease, forcing them to further aggravate the degradation of resources[20] (Figure 1.1). Regarding the world's natural resources, certain limits have already been exceeded, notably in terms of biodiversity and nitrogen and phosphorus cycles [ROC 09].

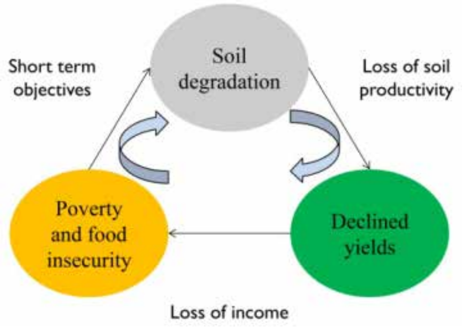

Figure 1.1. *Theoretical soil degradation spiral*

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[20] We will see in Chapter 3 that this poverty–degradation relationship is not universal.

This pessimistic view continues to be opposed by a more optimistic view, which was first defended by Condorcet (see previous section), based on the principle that communities facing diminishing resources innovate and adopt more productive practices per unit of surface area and labor (see Chapter 3). However, there are many archaeological examples that refute this hypothesis, since many communities have collapsed as a result of the degradation of their resources [DIA 05]. Nevertheless, this current stream of thought considers that technological progress, GMOs, sensors and connected objects, and above-ground agricultural production[21] should reduce pressure on cultivated land and thus promote better soil conditions. This vision is particularly based on the growth theory by Simon Kuznets (1901–1985), who received a Nobel Prize in economics in 1971, and his inverted U-curve. This describes the relationship between a country's level of development (measured in GDP per capita) (on the abscissa) and its level of inequality (on the ordinate). In an initial phase, this level of inequality would increase before decreasing once a development threshold is reached. Within this curve, the level of inequality can be replaced by other variables, such as population density or the percentage of deforested areas. This inverted U-shaped curve would present an analogy with the demographic and forest transition curves, with the hypothesis that environmental degradation [ALM 15, PAN 16] could follow such a trend (Figure 1.2), even if it remains differentiated according to the stage of economic development of the countries.

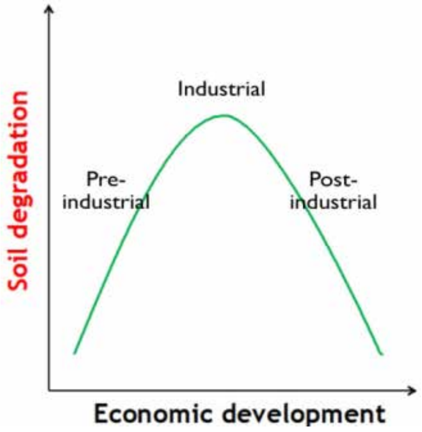

Figure 1.2. *The Environmental Kuznets curve: a development–environment relationship (adapted from [PAN 16])*

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[21] See the final chapter of *Soils as a Key Component of the Critical Zone 1: Functions and Services*.

1.2.5. *The necessity for monitoring mechanisms*

Between these two “pessimistic” and “optimistic” visions, it remains rather difficult to decide on one or the other since both are based on admissible hypotheses. However, they are not based on the same variables (and rarely on soil data), nor on the same time scales (short, medium and long term) and space scales (state level, or global scale). A global soil monitoring system based on regular time step sampling and standardized measurements is clearly lacking. Such systems were set up in the United Kingdom with sampling campaigns in 1978, 1998 and 2007 (591 sampling points [EMM 10]). In France, a soil quality measurement network (RMQS, *le Réseau de Mesures de la Qualité des Sols*, the Soil Quality Monitoring Network) was launched in 2000 with systematic sampling (including cities) using a 16 km square grid and 2,240 sampling points [SAB 14]. The second campaign began in 2016[22]. A similar, but probably less dense, system is essential on a global scale. It has so far not received the necessary international support, even though more than two-thirds of the earth’s soils are still not mapped at a scale finer than 1/1,000,000 [MDT 08], a scale necessary for soil characterization and monitoring.

1.3. Conservation, restoration, rehabilitation and compensation

This volume is entitled *Degradation and Rehabilitation* to highlight two opposing trends in soil condition, while maintaining a relatively short title. As shown in section 1.3.1, there are, in fact, other forms of soil enhancement than rehabilitation (Figure 1.3).

1.3.1. *Definitions*

Conservation involves the use of practices that maintain soil condition by preventing degradation, hence the term *prevention*.

Restoration aims to restore the soil to its original state in all its components and functions. It is generally only possible during its first phases of degradation.

Mitigation seeks to slow, and possibly reverse, ongoing degradation by improving the functions of already degraded soils. The term *remediation* is also used.

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[22] See Chapter 2 of *Soils as a Key Component of the Critical Zone 1: Functions and Services*.

Rehabilitation concerns already very degraded soils. It aims to reverse the trend, but has no ambition to return it to its initial state. It often requires more expensive investments than restoration and mitigation.

Compensation may be considered, as a last resort, in the event of the inevitable loss of productive soil as a result of urban sprawl or the construction of infrastructure (airport, motorway, dams, etc.), by offering its user an equivalent soil[23]. Be that as it may, although the principle of ecological compensation is already difficult to implement, it is even more so for soils, which, unlike fauna and even flora, are not transportable.

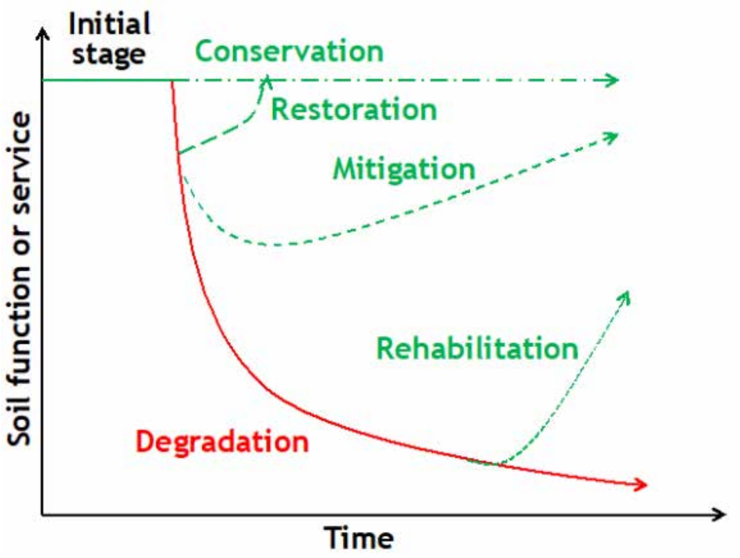

Figure 1.3. *Possible interventions to address soil degradation*

1.3.2. *Implementation*

Conservation, restoration, mitigation and rehabilitation practices depend on the forms of degradation and are presented in the different chapters of this book.

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[23] See Chapter 6 of *Soils as a Key Component of the Critical Zone 2: Societal Issues.*

The World Overview of Conservation Approaches and Technologies (WOCAT)[24] identifies the main soil conservation and improvement techniques adapted to different socioeconomic environments and situations.

1.3.3. *Concept of neutrality in terms of land degradation*[25]

The UN Convention to Combat Desertification (UNCCD) stresses that the annual cost of land degradation (US$490 billion) far exceeds that of land conservation. It promotes the concept of "land degradation neutrality" (LDN) in the form of a "zero net land degradation rate", which could be achieved by:

– managing land in a more sustainable manner, which would reduce the intensity of degradation (conservation, restoration, mitigation);

– increasing the percentage of rehabilitation of degraded land, so that the degradation versus rehabilitation balance becomes zero.

This international slogan has the merit of drawing the attention of the public authorities of various countries to the degradation of their soils, and to the need to reverse the current trend of degradation. It is based on the premise that part of the degradation is inevitable, if only for urban sprawl, and that it must be compensated by the rehabilitation of soil that is already degraded. This principle is included in the United Nations' sustainable development objectives[26] for 2030 and is the subject of a special fund (LDN). It is within this framework that baseline mapping of land degradation must be carried out in each country, taking land cover, land use change, soil productivity change and the organic carbon content of soil into account.

This concept of "neutrality" is problematic because it confirms the current level of soil degradation that, as we have seen above, is already very high. At best, the objective is to maintain this level of degradation. However, it is a first step, by imposing compensation for soil degradation which, at present, is still not regulated. Moreover, this middle-term objective is probably more realistic than the ambition to stop all forms of anthropogenic

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[24] Available at www.wocat.net.

[25] Available at https://www.unccd.int/actions/achieving-land-degradation-neutrality.

[26] Available at https://www.un.org/sustainabledevelopment/.

soil degradation. Nevertheless, it is a real challenge, as there are so many scientific obstacles. For example, the variables taken into account only make it possible to monitor a fraction of the forms of degradation. In particular, there are no mechanisms in place to monitor soil erosion, acidification and salinization. As Chapter 3 points out, a tree canopy does not guarantee, for example, that there will be no erosion. In addition, Chapters 6 and 7 show that soil productivity (one of the criteria) can be associated with serious pollution problems. The concept of neutrality in terms of land degradation also raises many political [GRA 15] – how do you resolve the many land use conflicts, economic – will the means be sufficient to ensure large-scale rehabilitation of degraded soils? and legal issues[27] – how can property rights be developed into user rights?

In some respects, the debate on neutrality in terms of land degradation is similar to that opposing the concepts of land sharing (with extensive agriculture and natural areas) and land sparing ("land economy", with intensive agriculture with little respect for the environment and more extensive natural areas) [FIS 14]. The concept of neutrality also has some analogies with the market for rights to pollute and the carbon market.

1.4. Conclusions

Soil degradation is a major challenge for the sustainability of the functions and services provided by the critical zone. However, the state of soils remains very poorly characterized on the global scale due to the lack of a reliable baseline and a system for monitoring relevant soil indicators.

However, it has been well established that soils have already undergone significant degradation, with a strong acceleration linked to deforestation in tropical regions and the intensification of agriculture (heavy motorization, synthetic nitrogen fertilizers, irrigation without drainage). In addition to these clearly identified causes, there are those related to urban sprawl, delta subsidence, climate change (melting permafrost, sea level rise), and changes in land use for non-food purposes (including biofuels).

It is imperative that the degradation curve be reversed so that soils continue to produce the functions and services that a rapidly growing world population

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[27] See the book *Soils as a Key Component of the Critical Zone 2: Societal Issues.*

requires of them. Although the international community is beginning to become aware of this (for example the international LDN fund), many uncertainties remain as to the resources mobilized for the rehabilitation of degraded soils and the implementation of a global monitoring system for the state of soils and their various forms of degradation. This instrument is essential for determining priorities, according to the needs of populations, and for regularly providing reliable data on the global state of soils.

RESEARCH QUESTIONS.–

1) What are the most relevant and usable indicators at different time and space scales in order to define the state of a soil?[28]

2) What are the rates of soil condition change (degradation/rehabilitation) for different forms of degradation and intervention (restoration, mitigation, rehabilitation) and what levels are likely to be achieved (Figure 1.3)?

3) What are the interactions between soil degradation/rehabilitation, population density and the stage of economic development of the regions or countries considered?

RECOMMENDATIONS.–

1) Remain cautious about global assessments of different forms of soil degradation due to high uncertainties related to the disparity in data quality and methods used (expert assessment, remote sensing, modeling).

2) Use experiments and long-term monitoring data to establish reliable trends in given contexts, without attempting to extrapolate them to other situations.

3) Formulate realistic recommendations, taking the objectives and constraints of the various operators into account in order to halt and reverse soil degradation.

1.5. References

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[28] Despite a great deal of work, the issue remains unresolved.

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