Chapter 3
The Role of Soil Information in Land Degradation and Desertification Mapping: A Review

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Abstract Mapping *land degradation and desertification* (LDD) has generally been considered as a complex task, and past efforts have produced contrasting results. Until recently, this exercise has often been seen as a soil scientist's task by the international community. However, the actual role and "weight" of soil information in LDD mapping at different spatial scales has been influenced and constrained by the changing conceptual frameworks and data availability. This chapter reviews these aspects and discusses the most recent developments. Starting from the evolving definitions of land degradation and desertification, it describes the use made of soil information by past global mapping initiatives. It presents the related past and new conceptual frameworks, and describes the approaches adopted by the most relevant ongoing international initiatives such as LADA and WAD. Finally, it highlights the existing constraints and limitations and provides recommendations on gaps and needs in terms of soil-related knowledge and data.

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3.1 The Evolving Concept and Definition of Land Degradation and Desertification

Since its coming into force, the *United Nations Convention to Combat Desertification* (UNCCD 1994) has stimulated and framed the international debate on *land degradation and desertification* (LDD). Desertification is defined by the Convention as "land degradation in drylands": in other words, desertification is a climatic sub-type of land degradation. However, the long-lasting debate that led to the UNCCD definition is still developing, and in need of a more science-based and rigorous definition. The related conceptual evolution has been discussed by several authors (Thomas and Middleton 1994; Eswaran et al. 2001; Le Houérou 2002; Herrmann and Hutchinson 2005; Safriel 2007; Reynolds et al. 2007).

The most recent tendency is towards defining desertification as "an end state of the process of land degradation, expressed by a persistent reduction or loss of biologic and economic productivity of lands" (DSD 2009). Its causes would be linked to both human and natural factors; these often act synergistically.

The underlying basic concept of "land degradation" has evolved over time too. Over the last thirty years land degradation concepts have moved from an initial emphasis on the productive capability of the soils to the all-encompassing concept of ecosystem capacity to provide goods and services to society. Some of the most recent definitions are listed below.

- The reduction or loss of the biological or economic productivity and complexity of the land resulting from land uses or from a process or combination of processes, including processes arising from human activities and habitation patterns (UNCCD 1994).
- The reduction in the capacity of the land to provide ecosystem goods, functions, and services that support society and development (MEA 2005).
- The reduction in the capacity of the land to provide ecosystem goods and services over a period of time for its beneficiaries (Nachtergaele et al. 2011).

According to the UNCCD, "land" means "the terrestrial bio-productive system that comprises soil, vegetation, other biota, and the ecological and hydrological processes that operate within the system".

Current ratification of the UNCCD reflects such a broader definition of desertification with the vast majority of the countries of the world declaring themselves as affected by desertification processes (Table 3.1). Among the 165

Table 3.1 Parties to the UNCCD and their status as affected or non-affected by desertification at the end of 2009. Roman numerals identify the five UNCCD Regional Annexes. *Source* The authors

Annexe	Affected	Non-Affected	Total no. of countries
1: Africa	53	0	53
2: Asia	51	5	56
3: LAC	33	0	33
4 and 5: Northern Mediterranean and/or Central and Eastern Europe	25	4	29
Non-annexe-specific OECD countries	3	19	22
Total	165	27	193

affected country Parties, 154 prepared a report as affected countries, and 103 have prepared their *National Action Programme* (NAP).[1]

Of the 193 UNCCD countries, 162 are developing countries (of which, 93 dryland-affected and 69 non-dryland-affected countries). The ratio of non-dryland to dryland developing countries rose from 0.33 in 1995 to 0.74 in 2004. Safriel (2007) discusses these figures and links this tendency with the increased funding opportunities that derive from institutions like the *Global Environment Facility* (GEF) or the *World Bank* (WB) that have included in their portfolios consistent amounts of funding for combating land degradation. Therefore, the tendency is to look at the UNCCD as a convention that deals with land degradation not just in the drylands but in all lands that could be at risk of degradation or are already degraded. This would represent a major shift for the convention and would give it a more global mandate.

Safriel (2009) discusses the links between desertification and drought and concludes that they are not straightforward and that the former does not necessarily precede the latter, illustrating this with examples from the Sahel droughts of 1968–1974 and 1983–1985. Again, the adoption of the DLDD (*desertification, land degradation and drought*) terminology shows that the UNCCD is struggling to adjust its actions to reflect its wider membership.

Obviously soil degradation, soil quality, and soil health play a crucial role in identifying areas affected by land degradation and desertification, and have been given varying definitions. The *World Reference Base for Soil Resources* (WRB) (FAO/ISRIC/ISSS 2006) describes the soil as:

> …any material within 2 m from the Earth's surface that is in contact with the atmosphere, with the exclusion of living organisms, areas with continuous ice not covered by other material, and water bodies deeper than 2 m.

Soil is the interface between earth, air and water and hosts most of the biosphere. It is essentially a non-renewable resource in that the degradation rates can be rapid whereas the formation and regeneration processes are extremely slow.

[1] See at: <http://www.unccd.int/en/about-the-convention/Action-programmes/Pages/default.aspx>.

Soil degradation is described by *physical, chemical, and biological degradation* processes acting upon the soil and impacting human well-being and livelihoods (Kaiser 2004). Each of these categories includes a set of degradation processes as described below:

- physical degradation: decline in soil structure, crusting, compaction, sealing, and erosion;
- chemical degradation: acidification, leaching, nutrient depletion, salinization, and alkalinization;
- biological degradation: depletion of soil organic matter, reduction of soil biodiversity, decline in activity and species diversity of soil fauna and flora.

A combination of some of these threats can ultimately propel arid or sub-arid climatic conditions towards desertification (European Commission 2006).

Given the conceptual differences between "land" and "soil", it is important to point out the distinction between "land quality" and "soil quality". Eswaran et al. (2003) state that the concept of soil quality is acceptable for plot- and farm-scale assessments, while land quality is appropriate for more general evaluations referring to national, regional, continental, or global scales. Land degradation often initiates when there is a mismatch between land quality and land use.

The same authors introduce the concept of *inherent land quality* (ILQ) and describe it as "the ability of land to perform its functions under natural conditions influenced only by the intrinsic properties of the ecosystem and not significantly modified by land management" (Eswaran et al. 2003). In addition to this concept they mention that of *managed land quality* (MLQ), which refers to the ability of land to function under managed conditions. The latter is very important since very few places on Earth have remained untouched by humans. The comparison between ILQ and MLQ indicates whether the natural equilibrium has been disturbed towards enhancement or degradation.

Another interesting concept that needs attention is *land resilience,* described as "the ability of land to restore to an acceptable level of performance subsequent to degradation" (Eswaran 1994). Resilience depends on soil-intrinsic fertility conditions as well as on the socio-economic and political situation where the land unit under consideration lies.

3.2 Recent Conceptual Developments

3.2.1 Ecosystem Goods and Services (G&S)

The ecosystem services framework is increasingly thought to provide a basis for assessing and valuing the impacts of land change and degradation, as well as the effects of the actions aimed at reversing it (DSD 2009). The major LDD processes, including water and wind erosion, soil salinization, loss of vegetation cover and diversity, and degradation of the hydrological cycles, are globally affecting the provision of ecosystem services (MEA 2005).

Ecosystem G&S, or ecosystem functions in general, were also claimed as a candidate for a unifying concept for ecology and economics (de Groot 1987). Ecosystem functions are defined as the capacity of natural processes to provide goods and services that satisfy human needs, directly or indirectly: so, they are "reconceptualized" as ecosystem goods or services when human values are implied (de Groot et al. 2002). The Millennium Ecosystem Assessment (MEA 2005) adopted the following G&S categories:

- supporting services (they support the provision of the other services): nutrient cycling, soil formation, primary production, etc.;
- provisioning services: food, fresh water, wood and fibre, fuel, etc.;
- regulating services: climate, flood, and disease regulation, water purification, etc.;
- cultural services: aesthetic, spiritual, educational, recreational, etc.

These G&S are linked to human well-being and security: the basic material for life, health, social relations, etc. (MEA 2005).

The analysis of ecosystem G&S is increasingly seen as an effective way of integrating relevant indicators to map the state and extent of LDD (Cherlet and Sommer 2009; Sommer et al. 2011). Specified key indicators can ideally reflect human–environment interactions and the associated ecosystem exploitation; hence their variation can be directly related to core ecosystem services, and, in most cases, the assessment of a specific ecosystem service will be a function of the combination and/or integration of several key indicators (Sommer et al. 2011; Zucca et al. 2012).

This approach emphasizes the role of soil information in LDD mapping. Soil is a very dynamic system that performs many functions and delivers services vital to human activities and to the survival of ecosystems.

The proposed EU Soil Framework Directive (European Commission 2006) establishes a framework for the protection of soil and the preservation of the capacity of soil to perform any of the following environmental, economic, social, and cultural G&S:

(a) biomass production, including in agriculture and forestry;
(b) storing, filtering, and transforming nutrients, substances, and water;
(c) biodiversity pool, such as habitats, species, and genes;
(d) physical and cultural environment for humans and human activities;
(e) source of raw materials;
(f) acting as a carbon pool;
(g) archive of geological and archaeological heritage.

To that end, it lays down measures for the prevention of soil degradation processes, both occurring naturally and caused by a wide range of human activities, which undermine the capacity of a soil to perform those functions. Such

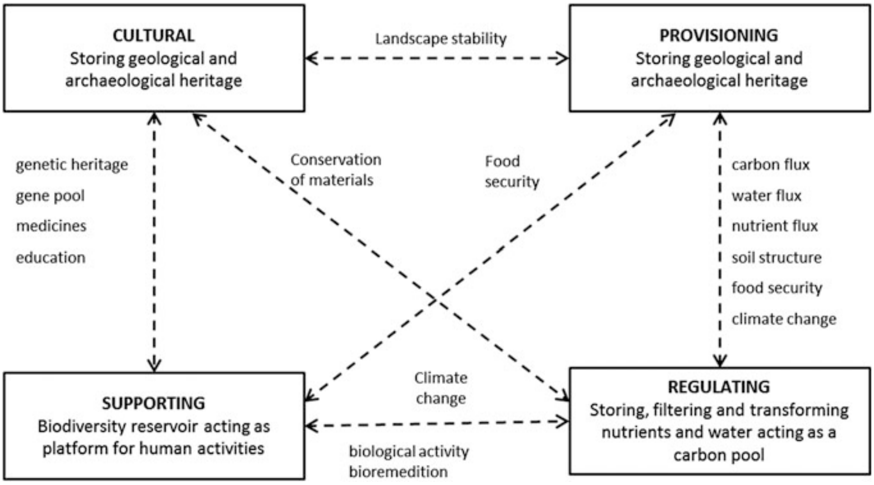

Fig. 3.1 Soil ecosystem services, soil functions, and their interdependencies. *Source* Unpublished material, courtesy of G. Toth

measures include the mitigation of the effects of those processes, and the restoration and remediation of degraded soils to a level of functionality consistent at least with current and approved future use.

The G&S identified in Europe may be as well considered for global assessments; nevertheless, a consistent list is still lacking and should form a core element of the revision of the World Soil Charter (FAO 1981) in the framework of the Global Soil Partnership, as proposed by FAO (2011). A more comprehensive discussion is developed by Toth and Nemeth (2011) and is summarized in Fig. 3.1.

3.2.2 The Anthroscape Concept

The "Anthroscape" concept as defined by Kapur et al. (2004) is a leading candidate for a robust basis for mapping land quality and sustainable land use patterns. This concept, since it embraces the components of the integrated environment, bears significance in assessing human-induced land degradation: understanding soil–landscape relationships in Anthroscapes helps to address LDD, especially when marked differences or deviations from the normal, natural landscapes are observed (Eswaran et al. 2011). Anthroscapes are the result of human impact on natural land- and soilscapes and are therefore typical of the Anthropocene (Crutzen 2002).

The approach is intended to help develop sustainable land management programmes and the introduction of the '*Anthroscape Land Quality Classes*–ALQC' to substitute the classical '*Land Capability Classes*–LCC' of land use of the US Department of Agriculture (Helms 1992).

The current LCC includes eight classes of land designated by the Roman numerals I to VIII. The first four classes are arable land (suitable for cropland) in which the limitations on their use and necessity of conservation measures increase from I to IV, depending on landscape location, slope of the field, depth, texture, and reaction of the soil. The remaining four classes may have uses for pasture, range, woodland, grazing, wildlife, and recreation. Subclasses signify limitations such as (e) erosion, (w) excess wetness, (s) problems in the rooting zone, and (c) climatic limitations. To designate classes not suited to continuous cultivation, the planners typically seize on classes from VI to VIII and subclasses IIIe and IVe. The question is whether the land capability classes, especially IIIe and IVe, are accurate and are a reliable method of identifying erodible land.

The "Anthroscape" context is based on a broader understanding than the LCC, and concentrates on the major issues related to soil loss at basin-wide scale and, thus, requires the integration of the baseline information concerning the topographic, vegetative, land use, demographic and socio-economic attributes with the information on traditional technologies and past land use, with a view to a holistic *sustainable land and water management* (SLWM) programme.

Understanding the soil–landscape relationships in Anthroscapes is a prerequisite for addressing land degradation and desertification. Conventional descriptions and analyses of soils may not suffice to address the subtle changes in soil attributes and functions. The ultimate outcome of the Anthroscape approach is the development of an 'Anthroscape Land Quality Class' map and the relevant 'Ideal Land Use Patterns'. These products are sought as a means of revealing the magnitude and the distribution of the degradation of the selected area, as well as allocating the ideal land use types. In a basin-wide scale, the downstream part of the map would show, so to say, the degradation arising via the intensive cultivation practices, where the class stated in the map would reveal the need of an integrated SLWM programme to revert the lower ALQCs to higher and more sustainable ALQCs. The *net primary productivity* (NPP) can be used via land cover and management as a supplementary indicator of the Anthroscape Land Quality.

3.3 Some Complex Aspects in LDD Assessment and Mapping

LDD takes on a multitude of complex forms and processes in each of the affected regions (Geist 2005) and is highly context-specific (Warren 2002). It can be difficult to take general decisions on which features are to be considered and mapped as LDD indicators, especially if the selected indicators must conserve their validity (and univocal interpretation) over wide areas (e.g. regional to global). This is a major factor explaining why the methodological debate on indicator selection has still not been resolved by the UNCCD (DSD 2009; Orr 2011).

Ecosystem *goods and services* (G&S) provisions are not necessarily evolving in the same direction and some may well improve while others decline. A simple example to illustrate this is the cutting down of a forest to make way for a road because of the needs of a developing economy. Such an intervention triggers a near-immediate decline of the ecosystem G&S. The biomass and a carbon sink disappear overnight, the soil is completely sealed or heavily disturbed, and ecosystem connectivity is affected. In the long run, the presence of this road may become an even more serious ecological threat, favouring penetration of human activities into the forest area, which can become detrimental to the integrity of the ecosystem. Economically, however, the land value is increased through an increased accessibility to markets and possible opportunities for the economic exploitation of the forest areas. The recreational use (and functions) of the forests may also be increased.

The above example also raises the question of the diversity of the G&S and for whom their provision is important. This means that it is necessary to take into account the interests of particular parties that may influence the definition of the concept of land degradation at any one particular time. When LLD occurs, it is often a matter of more concern to some groups of stakeholders than to others, including future generations whose opinion cannot yet be heard.

G&S provided by the land ecosystems also need to be operationally defined, in a way that allows quantification and integration/trade-off between very heterogeneous assets, from economic goods to inspirational services.

LDD is a dynamic process; it involves a change over time in the functioning of the land ecosystem due to human or natural pressures. In this process the land changes from a given state to another, where a decline in functioning is considered as degradation. This implies that a timescale must be set to evaluate LDD, as well as a benchmark baseline against which the changes can be compared.

There is no agreement on the timescale or the baseline year. A pragmatic approach could be to refer to the time span scientifically documented in terms remote sensing and climatic data, about 40 to 50 years maximum. The GLASOD (*Global Assessment of Soil Degradation*) project Oldeman et al. (1990) made an assessment covering the 25 years up to 1990, presumably based on human memory.

Another question is related to the sometimes difficult distinction between ongoing land degradation and degradation inherited from the past. Land degraded in the past may be stable now if pressure factors are no longer active. Furthermore, the productivity of some soils is naturally constrained, as for the natural saline soils. Confusing these stable “bad lands/problem soils” with land presently undergoing bad management and affected by degradation processes would be misleading.

It is often difficult to obtain evidence that past conditions were better than present and that presumed degradation was due to recent or present land use.

Finally, concerning the new definitions proposed for desertification, conceptual and practical problems arise from expressions such as “end state of the process of degradation” and “persistent reduction” because it is problematic to assign them an objective meaning. The same can be said for the distinction between reversible and irreversible conditions, although some authors still claim that what distinguishes desertification is its irreversibility (Santini et al. 2010).

3.4 The Role of Soil Information in Past LDD Mapping

3.4.1 Global Mapping

Mapping land degradation and desertification has generally been considered as a complex task. Past efforts have produced contrasting results, due also to evolving assumptions and methods. The never-ending debate on definitions, along with the scarcity of suitable global datasets, make LDD mapping a real conceptual and operational challenge (Sommer et al. 2011; Zucca et al. 2011).

Several global maps have been drawn since the 1970s, as reviewed by Grainger (2009). Most of the LDD maps produced so far have also been based on expert knowledge (especially mapping of LDD status), or on simple empirical models (mostly adopted to map LDD sensitivity). Among these we can mention:

- the Global Map of Desertification Status (Dregne 1977, 1983);
- the FAO/UNEP Provisional Methodology for Assessment and Mapping of Desertification (FAO/UNEP 1984);
- the Global Assessment of Soil Degradation (GLASOD; Oldeman et al. 1990);
- the UNEP World Atlas of Desertification (UNEP 1992, 1997);
- the Global Desertification Vulnerability Map (USDA 2003).

Apart from the FAO/UNEP (1984) Methodology that mixes status and risk factors, and the US Department of Agriculture (2003) Vulnerability Map, the others are mostly based on expert evaluations of current LDD status. These expert judgements are then usually "attached" to different kinds of predefined map units (either pre-existing or purposely created by overlaying sets of maps). The approaches adopted are most often oriented to reporting on the occurrence of land degradation processes, with a special emphasis on soil degradation. The degradation processes and the related indicators considered by some of these studies are summarized in Table 3.2.

Until recently, GLASOD (Oldeman et al. 1990) was the only global study to estimate the extent of human-induced soil degradation (Fig. 3.2). It discovered that out of the 11.5 billion hectares of vegetated land on Earth, 17 % was degraded largely by erosion, and on this land one in six hectares could no longer be cultivated. The main causes of this environmental disaster were deforestation and adverse farming practices such as overgrazing and nutrient mining. GLASOD estimates are mostly based on expert assessment, but it deserves credit because it contributed greatly to bringing the issue of soil degradation to higher political and decision-making levels.

Other studies that could be mentioned for the inputs and the results they produced at regional scale are the *Assessment of human-induced soil degradation in South and South-East Asia* (ASSOD) (van Lynden and Oldeman 1997), *Digital Geo-referenced database of soil degradation in Russia* (Stolbovoy and Fischer 1997), and *Soil Degradation in Central and Eastern Europe*—SOVEUR (van Lynden 2000).

Table 3.2 Indicators taken into account by some global LDD mapping studies. *Source* The authors

	Processes and factors assessed	Dregne (1977)[1]	FAO/UNEP (1984)[2]	Oldeman et al. (1990)[3]	UNEP (1992)[4]
Soil	Water erosion			X	
	Erosion occurrence				X
	Gullies (number and shape)	X			
	Gully area		X		
	Surface status (stones, rocks…)		X		
	Soil thickness		X		
	Loss of soil depth over root-inhibiting layer		X		
	Eroded area/subsoil exposed		X		
	Wind erosion		X	X	
	Dunes (size, vegetation cover, mobility	X			
	Chemical degradation			X	
	Organic matter reduction		X		
	Salinity	X	X		
	Physical degradation			X	
	Soil crusting and compaction	X	X		
Vegetation	Vegetation degradation				
	Undesired shrubs	X			
	Fall in cover and composition		X		
Yield/productivity	Farm yield decrease	X			X
	Terrain suitability to local farming				X
	Ease of restoring yields				X
	Ease of restoring terrain				X
Ecosystem	Biotic functions				X

[1] Simple indicators related to four processes (e.g.: "many large, deep gullies"; "undesired shrubs") are assessed in three broad land use classes (rangelands, rain-fed croplands, and irrigated croplands) to define four degrees of desertification severity

[2] Four degrees of desertification severity are assessed based on the evaluation of status, rate, and inherent risk related to six processes. Due to the number of indicators considered, the table only reports the status factors related to water erosion. For this process, the rate is related to the decrease in annual biomass production, the increase in eroded area and soil loss, the sediment deposition in reservoirs, and the related loss of storage, while risk is linked to the climatic aggressivity, the pedo-topographical conditions, and the potential soil erosion

[3] Degree and extent of degradation are assessed for each soil degradation process (four categories, each including several specific indicators) in each of a predefined set of mapping units, to estimate four degrees of desertification severity

[4] Five degrees of desertification severity are considered. Land degradation, and in particular soil degradation, is assessed in two land use systems (rangelands and rain-fed croplands) based on five indicators. These are mostly related to the LDD impact on land functions and health, and on the recovery potential

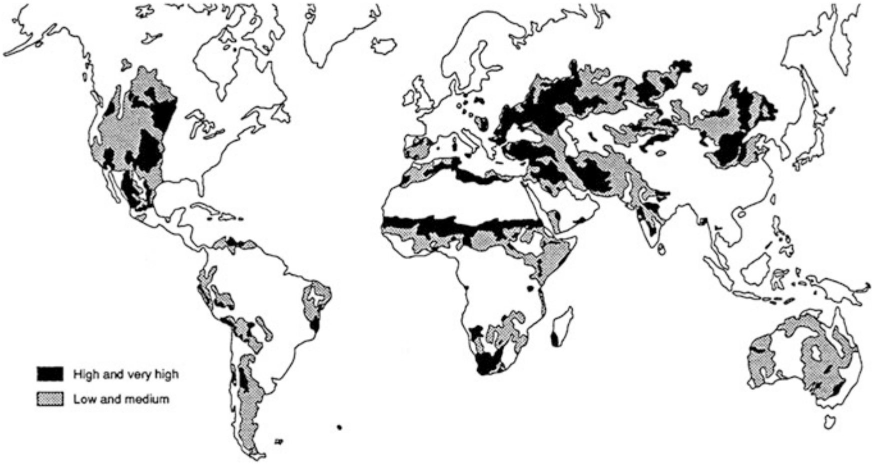

Fig. 3.2 GLASOD, global extent of human-induced soil degradation. *Source* GLASOD

Based on GLASOD, Lal (2003) presented soil degradation data on continental bases and by type of degradation processes (Table 3.3).

3.4.2 Regional to Local Scale Mapping Through Empirical Models

Empirical models have been widely used to combine indicators to perform LDD mapping at various scales, in particular to assess areas prone to desertification. National risk mapping studies were performed in many countries in the frame of the UNCCD implementation, as reviewed for the Northern Mediterranean region (Table 3.4) by various authors in Enne et al (2004), and worldwide by Enne and

Table 3.3 Estimates (millions of ha) of the global extent of soil degradation by different processes. *Source* GLASOD

Region	Total land area	Total degraded area	Total degraded area (%)	Water erosion	Wind erosion	Physical degradation	Chemical degradation
Africa	2,964	494	17	227	186	19	62
Asia	3,085	749	24	441	222	12	74
S.America	1,753	243	14	123	42	8	70
C. America	108	63	58	46	5	5	7
N. America	2,029	96	5	60	35	1	–
Europe	2,260	218	10	114	42	36	26
Oceania	849	102	12	83	16	2	1
World	13,048	1,965	15	1,094	548	83	240

Table 3.4 The indicators considered by the national risk mapping studies performed in the frame of the UNCCD implementation by Northern Mediterranean countries between the late 1990s and the early 2000s. *Source* The authors

Scale	Portugal 1:1,000,000	Spain 1:1,000,000	Italy 1:1,250,000	Greece 1:1,000,000	Turkey 1:1,000,000
Climate	Aridity index P/PET	Aridity index P/PET	Aridity index P/PET	Bioclimatic zones	Annual rainfall; Aridity index P/PET
Soil	Potential soil loss based on four indexes (rainfall erosivity, slope, land use and soil type)	Potential soil loss due to erosion based on *Universal Soil Loss Equation* (USLE) approach	Soil moisture regime	Soil depth and erosion risk based on soil map units and slope; soil salinity based on soil map units and bioclimatic zones	Soil moisture deficiency (Thornthwaite water balance); soil loss (% of topsoil lost)
Vegetation			Land cover classes	Vegetation resilience in bioclimatic zones	NDVI-derived vegetation cover
Drought	Frequency and intensity of drought			Edaphic drought risk related to soil map units and bioclimatic zones	Annual rainfall variability
Demography			Decadal demographic change 1981/1991		
Acquifers over-exploitation		Acquifer pumping and recharge ratio		Irrigation intensity and salt seawater intrusion	
Forest fires		Wildfires occurrence 1986–1995			Fire risk estimated based on fire occurrence per land unit

Yeroyanni (2006) and Begni et al (2007). An attempt was made to integrate the indicators listed in Table 3.4 (with the exception of Turkey) into an overall desertification risk index for all the countries, based on various empirical approaches. In Table 3.4, qualitative, expert-based indicators still coexist with quantitative (although simplified) indicators, but the latter dominate at this spatial scale.

In 2008, the European Environment Agency also produced a map at a scale of 1:1,000,000 showing the sensitivity to desertification for the Northern Mediterranean using a composite evaluation of soil, climate, and relief characteristics, but no socio-economic analyses were considered (EEA 2008).

More sophisticated empirical models were developed to map desertification risk at the local scale. The ESA-Medalus model (Kosmas et al. 1999) is the most widely applied and proved to be flexible enough to be adapted to many different situations (Sepehr et al. 2007; Santini et al. 2010. The soil indicators considered by that model are partly quantitative and partly qualitative: internal soil drainage; texture class; soil depth; rock fragments at the soil surface. These are combined with slope gradient and bedrock type to produce a "soil quality index" by means of map algebra procedures implemented in a *geographical information system* (GIS) environment.

3.4.3 Approaches Based on Vegetation Cover Status as Driving Variable

Some recent efforts to define land status at a small geographical scale have been based on a single index or only a few, such as *Normalized Difference Vegetation Index* (NDVI) (Helldén and Tottrup 2008), NPP (Boer and Puigdefabregas 2005), *rain-use efficiency* (RUE) (Bai et al. 2008), and other statistically more complex methods (Wessel et al. 2008; Del Barrio 2010). These approaches have demonstrated that the interpretation of the results obtained may depend on assumptions that do not conserve their validity over large geographical areas.

A feature common to these methods is that they primarily link LDD trends to vegetation status trend, and do not explicitly consider soil conditions.

3.5 The LADA Project

Since 2006, the *Land Degradation Assessment in Drylands* (LADA[2]) project has been developing and testing a new method for mapping land degradation and land improvement on the basis of a mix of factual data and expert knowledge.

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[2] See at: <http://www.fao.org/nr/lada/index.php>.

The method has been conceived and tested at national level in six countries (Argentina, China, Cuba, Senegal, South Africa, Tunisia), covering an area of about seven million square kilometres. It is based on the principle that land use is the main driver of land degradation or land improvement. The method consists of two main steps: (1) the creation of a land use systems map, and (2) the collection of information on the status and trends of land degradation within each of these units.

3.5.1 The Land Use Systems Map

Land use system (LUS) units, according to the LADA methodology (Nachtergaele and Petri 2008), are based on a land cover base with the addition of information on irrigation, livestock, and protected areas. Additional information can be utilized, if available, for further refining the map. This extra information can be attached as an attribute to the unit, in order to have a set of data that allows for a better identification and enhanced explanation of the spatial distribution and the reasons for the land degradation and land improvement. The LUS units are then overlaid with a map of administrative units of the country. The final result consists of LUS units within administrative boundaries. These are the cartographic units for the mapping of land degradation and land improvement at subnational level.

The LADA project has created an LUS map at global level (Fig. 3.3). Each of the participating countries also produced their own national LUS map.

3.5.2 The Collection of Information on Land Degradation and Land Improvement

On the basis of the LUS map, a panel of experts in the country collects and summarizes the available information and knowledge on land degradation and land improvement in each of the LUS units. The method encourages the national panel to collect as much existing hard information as possible in terms of maps, datasets, and statistics. This land degradation information is then attached to the LUS map. This is done through the application of a questionnaire for each cartographic unit (Liniger et al. 2013). The questionnaire includes more than seventy indicators or descriptors of status, causes, and trends of land degradation and improvement status and processes. It is divided into four parts: (1) analysis of the land use system itself, (2) the types, causes, and impacts of land degradation, (3) the measures for combating degradation that are in place, and (4) the recommendations that the evaluation panel proposes for further improvement.

The final output is a georeferenced database containing hundreds of pieces of information on the situation of land resources. More than eighty single-factor maps

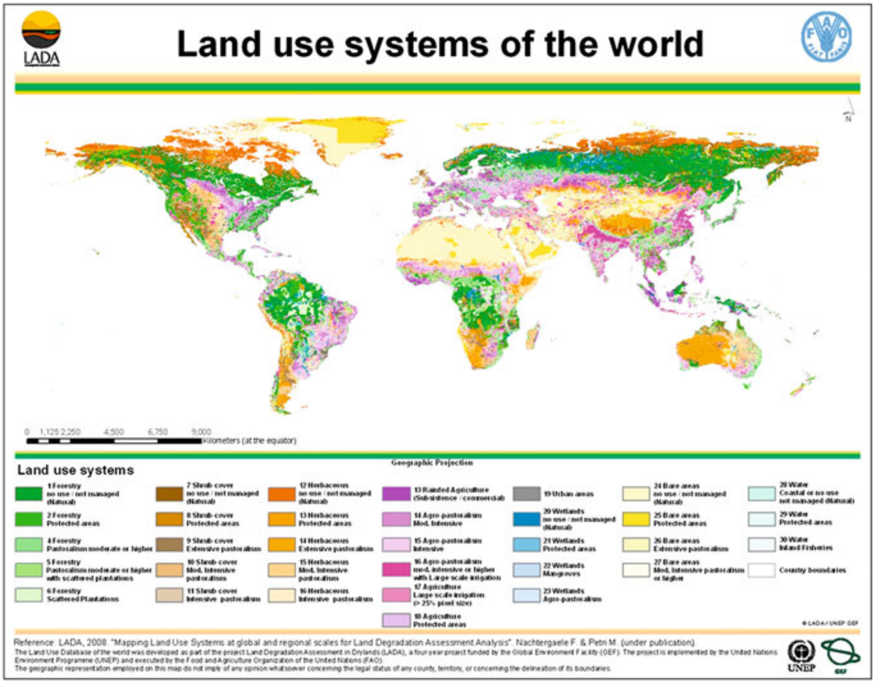

Fig. 3.3 The global Land Use System (LUS) map produced by the LADA project. *Source* Redrawn by the authors, based on unpublished data

can be directly produced from it, giving the possibility of a depiction of the causes and impacts of land degradation at subnational level, according to the *Driver-Pressure-State-Impact and Response* (DPSIR) approach (Gentile 1998). An example of map of land degradation (Land degradation in Senegal—degree of topsoil loss) is given in Fig. 3.4.

3.5.3 Comparison with GLASOD and Role of Soil Information

Although it is recognized that a fully objective assessment of land degradation, based on hard data, is not yet possible (Sonneveld and Dent 2009; Orr 2011), differences do exist between the LADA and GLASOD approaches. Firstly, GLASOD only considers soil degradation, while LADA also takes into account changes in other important ecosystem provisions such as water and vegetation, as well as considering social and economic issues. Secondly, while GLASOD was based on the personal knowledge of a restricted number of experts, LADA relies on panels of specialists from various disciplines, well rooted in their countries,

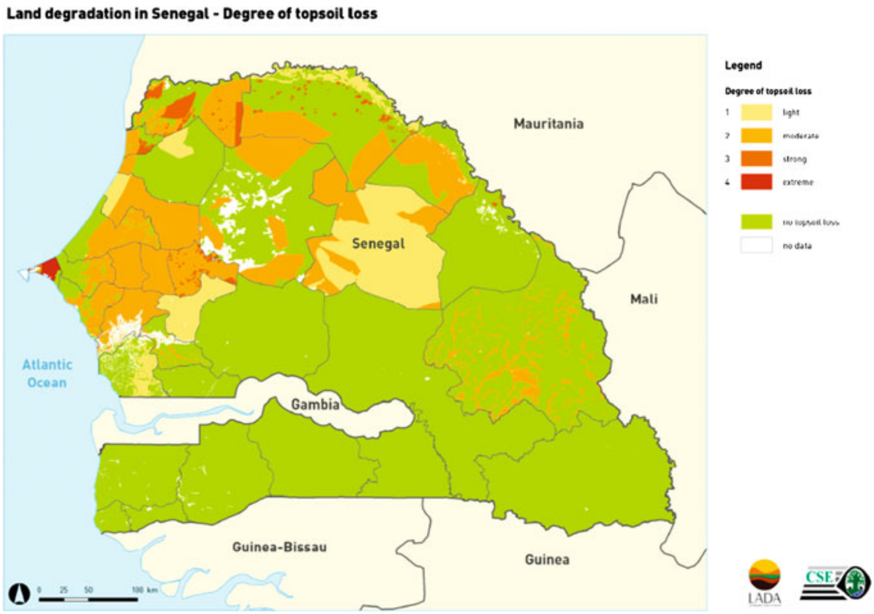

Fig. 3.4 Example of map of a land degradation factor as produced by the LADA project at the national level (Land degradation in Senegal—degree of topsoil loss). *Source* Redrawn by the authors, based on unpublished data

often working at subnational level. The detail and the accuracy of the assessment are therefore greatly increased. Finally, the use of the LUS map and of existing information reinforces the robustness and consistency of the final product.

As stated, LADA considers several aspects of land resources. Nonetheless, soil information still has an important, and sometimes dominant, role in the assessment of the situation and of the possible solution to the problems identified. Soil information is used at two stages of the subnational LADA assessment:

- in the assessment of land degradation, soils are regarded in detail in terms of their physical, chemical, and biological properties and characteristics, which vary from water and wind erosion, salinization, and compaction to alkalinization and many others;
- in terms of pedological information, which is an important attribute that can be attached to the LUS map, allowing a better spatialization of the information on degradation.

3.5.4 Gladis

Parallel to the system for data collection at subnational level described above, the LADA project has developed a system for land degradation assessment at global level, named GLADIS (*Global Land Degradation Information System*; Nachtergaele et al. 2011). GLADIS aims at providing an overview of the status of the land resources and of the processes that act on them, leading either to land degradation or improvement.

Similarly to the subnational system, GLADIS is based on the principle that land use, and in particular land use change, is the main factor leading to land degradation. Hence, a global map of land use systems is also the basis for the interpretation of the outcome in GLADIS. Unlike the subnational system, however, the LUS is not used as the cartographic basis for an expert assessment. On the contrary, in GLADIS the information on natural resources is provided by a series of 32 global datasets, some of them produced by the LADA project, the others collected among several institutions, organizations, and publications. The data have been harmonized into a grid of 5 min of arc.

The information collected in this way is utilized to analyze the status and processes of six main ecosystem "assets", or goods and services: biomass, soil, water, biodiversity, economic, and social. The analysis is done through mostly empirical models, different for the status and for the processes. The models are partially tailored according to the LUS unit, in order to produce results in stronger accordance with the actual reality.

Soil information has a very important role in GLADIS. The status of the soil resources is determined essentially as a soil suitability assessment, on the basis of the actual use of the land. In this way, the risk is avoided of considering certain soils as "good" irrespective of the present cover, so creating the risk of poor decisions based on wrong assumptions. A typical case is the soil under forest, which is usually considered very healthy while the forest remains standing on it, but no assumptions are made where there is a change in land use.

In the GLADIS system, both the chemical (salinization, pollution, and nutrient depletion) and the physical (erosion and compaction) degradation processes are considered. The two groups are then combined to create an index of soil resilience to degradation.

A management index, based on the production performance of the land in agricultural areas, is defined to identify areas potentially undergoing an improvement in the soil conditions.

Two final soil health indexes (status and process) are produced (Fig. 3.5). Together with the other ten indexes (status and process for each of the other five ecosystem assets), they define the overall degradation indexes, again to be analysed on the basis of the land use system units.

3.6 The New World Atlas of Desertification

In response to the interest expressed by the UNCCD *Committee on Science and Technology* (CST) in an updated *World Atlas of Desertification* (WAD), the European Commission's *Joint Research Centre* (JRC), in partnership with UNEP,

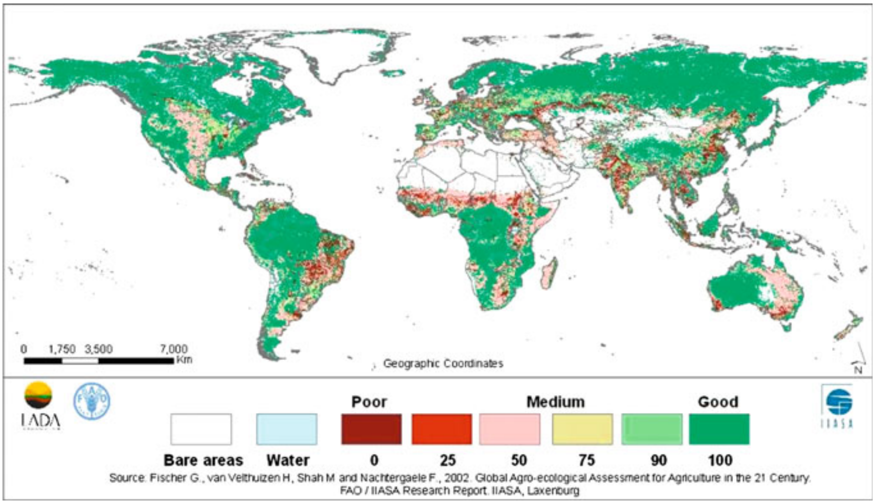

Fig. 3.5 One of the two soil health indexes (status and process) produced by GLADIS: soil health status for present land use. *Source* Nachtergaele et al. (2011). Redrawn by the authors, based on unpublished data

is coordinating the compilation of a new atlas to be ready by the end of 2012 (Cherlet and Sommer 2009; Sommer et al. 2011). The WAD will provide a foundation for addressing the global challenges related to desertification and has the goal of documenting the status of desertification, land degradation, and drought (DLDD) and the factors that influence these processes, and of providing their extent and spatial distribution at various scales: global, continental, regional, and in some cases even at national level. To address the issue of national and especially local scale, the WAD will provide a number of case studies that will be carefully selected to offer worldwide geographical coverage and thematic relevance. The WAD pays particular attention to land use changes and their impacts on ecosystem services.

In the context of WAD preparation, the establishment of a Working Group on "Soil" was proposed at the third Expert Meeting (December 2010). This Working Group will focus on the functioning and impacts of soil and its changing characteristics (constraints and soil degradation), on the human–environment system, and specifically on productivity levels (that is, NPP). Soil constraints and degradation will include a comprehensive assessment and analyses of:

- soil salinization, focusing on impacts related to irrigation;
- water, wind erosion, and sand encroachment, with a major focus on the impacts of unsustainable land use systems reflected in loss of productivity and disruption of ecosystem services;
- organic matter decline and nutrient depletion in arable lands (nutrient mining);
- soil sealing/urbanization as factors in the disruption of water and nutrient cycles affecting both food security and ecosystem stability; and

- soil–water relationships in the drylands, with a major focus on water scarcity as a limiting factor for crop production.

Global maps describing the above transitional processes will be included. The major focus will be on the drylands, so that the intensity of degradation between them and the remaining more humid global areas may be compared.

3.7 The Present Global and Regional Availability of Soil Data

The global situation of soil data availability, be it in the form of soil maps, soil profile information, or chemical, physical, and biological soil characteristics, is unsatisfactory. For too long soils have been seen as a simple substratum in which plants could grow and where water and carbon could be stored. This has resulted in scant investments in soil and soil knowledge over the last forty years. This situation has been further complicated by a number of factors:

- There is no international agreement on how to measure soil properties or on which ones are of prime importance. This has resulted in a multitude of results measured at different times in different ways that cannot easily be compared or correlated.
- Until 1998 there was no international agreement on soil nomenclature. The World Reference Base for Soil Resources established by the IUSS (*International Union of Soil Science*) in 1998 was supposed to end the nomenclature controversy, but it was challenged in several international meetings, making it inapplicable worldwide.
- Soil data are considered valuable and/or private information in many countries and access to national and local soil information can be difficult or expensive to come by.
- There remains a large gap of scientific misunderstanding and economic competition between soil scientists who produce "classical" soil maps using polygons to represent soil associations and those who use "modern" approaches that focus only on point information about certain soil properties.

3.7.1 Availability of Global Soil Maps and Databases

At the global level, the 1:5,000,000 scale Soil Map of the World (FAO-UNESCO 1971–1981) was, until recently, nearly thirty years after its finalization, the only worldwide, consistent, harmonized soil inventory that was readily available in digital format and came with a set of estimated soil properties for each mapping unit (FAO 1995). The digital raster version of this map had a resolution with a $5' \times 5'$ cell size (9 km × 9 km at the equator), and contained a full database corresponding to the information in the paper map in terms of composition of the soil units, topsoil texture, slope class, and soil phase in each of the more than 5,000 mapping units. In addition pedo-transfer functions allowed further characterization of each unit in terms of chemical and physical properties. This product has been updated over the years, mainly by regional and national efforts under the SOTER (*SOil and TERrain Database*—Van Engelen and Wen 1995) programme run by *International Soil Reference and Information Centre* (ISRIC) and FAO, the production of large regional databases for Europe and the northern circumpolar areas driven by the EU, Russia, and the USA, and efforts by large countries to produce national soil maps, as carried out by China. These updates were brought together in 2008 in the *Harmonized World Soil Database* (HWSD) that combines the recently collected regional and national updates of soil information with the information already contained within the 1:5,000,000 scale FAO-UNESCO Digital Soil Map of the World (FAO/IIASA/ISRIC/ISSCAS/JRC 2008). In order to estimate soil properties in a harmonized way, in this product the use of actual soil profile data and the development of pedo-transfer rules was undertaken in cooperation with ISRIC and the *European Soil Bureau Network* (ESBN), drawing on the ISRIC-WISE soil profile database and earlier work of Batjes et al. (1997, 2007) and Van Ranst et al. (1995). A resolution of about 1 km (30 s of arc by 30 s of arc) was selected. Over 15,000 different soil mapping units are recognized in the HWSD.

The resulting raster database consists of 21,600 rows and 43,200 columns, which are linked to harmonized attribute data. The use of a standardized structure allows linkage of the attribute data with GIS to display or query the map unit composition in terms of soil units and the characterization of selected soil parameters (organic Carbon, pH, soil moisture storage capacity, soil depth, cation exchange capacity of the soil and the clay fraction, total exchangeable nutrients, lime and gypsum contents, sodium exchange percentage, salinity, textural class, and granulometry). The HWSD map, database, and a viewer are available on CD-ROM and freely downloadable from <http://www.fao.org/nr/land/soils/harmonized-world-soil-database/en/>.

The main advantage of these two products is that they are readily and freely available and provide sufficient soil information for global purposes that require information on soil fertility levels, water-holding capacity status (for instance required for Global Circulation Models), or Carbon stocks. Disadvantages are that:

- the reliability of the information presented on the HWSD is variable and depends on the scale/resolution of the source data;
- the approach both in the *Soil Map of the World* (SMW) and the HWSD remains polygon-based and is therefore difficult to translate into point information within the polygon;
- data cannot be used for monitoring purposes and should not be used as a basis for local development plans.

3.7.2 Harmonized Global Soil Profile Databases

In the early 1990s, ISRIC developed a uniform methodology for a global soil database in the framework of a project entitled *World Inventory of Soil Emission Potentials* (ISRIC-WISE). WISE was especially conceived for a geographical quantification of main soil factors that control processes of global change at a broad scale (Batjes and Bridges 1994; Batjes et al. 1995).

In the process of collating materials for compilation of the ISRIC-WISE profile database the quality and validity of the original data had to be evaluated carefully, while at the same time recognizing that these are the only materials available. The description status of the various profiles has been documented in WISE to provide a coarse indicator for the inferred reliability of the source data (Table 3.5).

The latest public domain release of WISE, version 3.1 (WISE3), comprises data for some 10,250 profiles with some 47,800 horizons, from 149 countries (Batjes 2008, 2009), as opposed to around 4350 profiles in an earlier version (Batjes 1999). Most profiles are from Africa (41 %), followed by Asia (18 %), South America (18 %), and Europe (13 %). Their approximate location is shown in Fig. 3.6.

Overall, chemical and physical analyses have taken place in at least 150 laboratories worldwide, using a range of methods; these are described in broad terms in WISE3. Analytical methods used in the *ISRIC Soil Information System* (ISIS) and the *National Soil Survey Center* (NSSC) collection may be considered to be similar (van Reeuwijk 1983). Conversely, for the other sources methods typically vary from one laboratory to the next, even within one country, and may change over time within a single laboratory. These methodological differences complicate the worldwide comparison of soil analytical data, and no single solution for addressing this issue has been found as yet (Batjes et al. 1997; van Reeuwijk 1983; Van Ranst et al. 1995). As a result, the amount of measured data available for modelling is much less than expected.

Table 3.5 Number of profiles in WISE3 by continent and their description status. *Source* Batjes (2009). Reproduced by permission of John Wiley and Sons

Continent	Profile description status[1]				Total
	1	2	3	4	
Africa	421	1,337	2,392	23	4,173
Asia	441	970	426	10	1,847
Antarctica	4	6	0	0	10
Europe	225	712	359	20	1,316
North America	495	222	127	11	855
Oceania	50	49	106	4	209
South America	149	1380	313	1	1,843
Total	1,785	4,676	3,723	69	10,253

[1] The number code under profile description status refers to the completeness and apparent reliability of the soil profile descriptions and accompanying analytical data for the specified profile in the original source; the status is highest for 1 and lowest for 4 (see FAO 2006). Continents are defined according to Times Atlas (2003)

Fig. 3.6 Global distribution of georeferenced soil profiles in WISE3. *Source* Batjes (2008). Reproduced by permission of ISRIC—World Soil Information

The WISE3 dataset is readily and freely available and serves as the main source data both for polygon maps/databases as discussed in Sect. 3.7.1 and for the digital soil mapping approaches discussed in Sect. 3.7.3. Given the uneven distribution in space and time of the profiles and the diversity of analytical methods used, these data cannot be considered independently as a harmonized global product of soil information.

3.7.3 Digital Soil Mapping

In 2006 a consortium of scientific institutes and universities launched an appeal to use the latest satellite technology and new information layers, such as the recently released topographical information at 90-metre resolution, to achieve a spatial database of soil properties based on a statistical sample of landscapes (GlobalSoilMap.net 2009). Within the sample of satellite sites, field sampling is used to determine the spatial distribution of soil properties in order to develop reflectance spectral libraries for the characterization of soil properties (Shepherd and Walsh 2002). These are then used to predict soil properties in areas not sampled (see McBratney et al. 2003; Lagacherie et al. 2006; Hartemink et al. 2008). The resulting digital soil maps describe the uncertainties associated with such predictions and, when based on time series data, can also provide information on dynamic soil properties. Maps derived from digital soil mapping differ from conventional polygon-based maps in that they are pixel-based and thus can be more easily displayed at a higher resolution than those currently used by other earth and social sciences (Sanchez et al. 2009).

The GlobalSoilMap.net (2009) project, funded by the Bill & Melinda Gates Foundation in 2008, started with a pilot covering sub-Saharan Africa. Regional nodes in other continents were also established. As summarized by Sanchez et al. (2009), GlobalSoilMap.net proceeds in steps with the ultimate aim of developing evidence-based soil management recommendations at very high resolution. During the initial stages of the project, only six soil properties are considered: clay content, organic carbon content, pH, estimated cation exchange capacity, electrical conductivity, and bulk density. These may be used to generate a range of maps, as discussed by Sanchez et al. (2009). Finally, spatially inferred soil properties are used to predict more difficult-to-measure soil functions such as available soil water storage, carbon density, and phosphorus fixation. This is achieved by using pedotransfer functions.

An innovative element of the approach is that the overall uncertainty of the prediction is determined by combining uncertainties of the input data, a spatial inference model, and the soil functions used.

The approach relies heavily on statistics and modern approaches to soil mapping (spectrophotometry, remote sensing), limiting the use of expensive systematic ground observations. It moves away from understanding the soil distribution in a landscape to achieving a statistical representation of soil properties for soil management purposes. Several pilot projects are under way to support the theories that underlie GlobalSoilMap. Conversely, as with any new approach, a number of scientific and operational challenges still need to be resolved; these have been discussed in detail by various authors (Lagacherie et al. 2006; Hartemink et al. 2008).

3.8 Data Gap and Needs and Recommendations for Global Soil Data Gathering, Survey, Processing, and Use

As illustrated in the previous section, there are significant gaps in global and regional soil information in terms of uniformity and harmonization. Furthermore, the coverage is uneven, with drylands, deserts, mountains, and Polar Regions having very few measured data, while regularly monitored soil data are lacking nearly everywhere. Resources for making new soil inventories are scarce and many national soil survey agencies have closed down in recent years. There are additional problems with making the soil information freely available in an easily accessible format. Problems are as much economic and political as they are scientific.

Overall there appears to be an urgent need to come to a binding international agreement on soil nomenclature and soil laboratory methods. This would need to be supplemented by accepting the complementarities of polygon-based and point-based approaches to classical or digital soil mapping as presently undertaken in the e-SOTER, DIGISOIL and iSOIL projects of the European Union. Due strengthening of national soil agencies and their full involvement in international initiatives is also a must.

This can only be achieved by a new agreement between all parties, as recently proposed under the *Global Soil Partnership* (GSP), that would bring into a coherent framework all current data collection and soil mapping efforts at the global scale. The main elements of the GSP, as proposed by FAO, will be a vigorous effort towards standardization and harmonization of data collection and soil mapping methodologies that combines the existing raster-based and polygon-based digital soil mapping projects into a single coherent framework. An essential part of this renewed effort will be the adoption of a new Universal Soil Classification system that will combine existing national and international systems into a single unified global standard.

3.9 Conclusions

Most of the global LDD status maps produced since the 1970s were aimed at reporting on the occurrence of degradation processes within predefined map units. Soil degradation was generally given a special emphasis, but the maps were mainly qualitative and based on expert knowledge. Some mapping exercises at greater scales, such as the studies performed by countries in the framework of the UNCCD, were mainly based on empirical models (especially the mapping of LDD risk) where qualitative and quantitative soil data coexisted.

Since most of these methods were oriented towards tracking processes, little attention was devoted to causes and to impacts on ecosystem G&S.

The most recent approaches (especially LADA and WAD) try to overcome these limitations. Both initiatives integrate innovative approaches to interlink causal factors and to represent the impacts on ecosystem G&S. LADA designed a sound conceptual framework for integrating qualitative and quantitative information. WAD will be based on hard data and will make full use of the new global soil datasets.

The degree of harmonization and availability of global soil data has considerably improved during the last few years. The development of pedo-transfer functions is helping to fill gaps in information, but there is an urgent need for updated and detailed data and information on policy-relevant soil parameters, particularly soil organic carbon content, soil erosion, salinization, contamination, compaction, soil biodiversity levels, and others. Unfortunately ongoing efforts at data collection are very limited and lack the necessary multi disciplinarity for addressing the policy-relevant issues at stake. In addition, competing initiatives and lack of standardization are generating unnecessary duplication of efforts and a waste of available resources. The new Global Soil Partnership started in 2012, with Secretariat at FAO could be the way forward towards the next generation of policy-relevant soil data and information at the global scale.

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