The use of soil organic carbon as an indicator of soil degradation

Soil degradation has drawn great attention in soil and land studies over the last decades. The status of soils has been usually analyzed according to their components, focusing on their physical and chemical properties and their changes. However, only recently there have been attempts to aggregate the information into the single concept of soil health, identifying the capability of soil to support the present land use. A healthy soil is in equilibrium with the cover it supports. When this equilibrium is broken, the soil health deteriorates and the soil degrades. The organic carbon content in the soil (SOC) has been proposed to be used as an indicator of the soil health level. Whilst SOC is surely very significant for such assessment, it should not be taken as a comprehensive indicator for all the aspects of soil health

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Uso del carbonio organico come indicatore del degrado del suolo

Il degrado del suolo ha suscitato notevole interesse negli studi dei tipi di suoli e terreni. Lo stato del suolo viene solitamente analizzato sulla base dei componenti e, in particolare, delle proprietà fisico-chimiche e le loro eventuali alterazioni. Tuttavia, recentemente si è assistito a tentativi di aggregazione delle informazioni nel concetto unico di salute del suolo, con il quale si intende la capacità del suolo di sostenere l'effettivo uso del terreno. Un suolo sano è in equilibrio con lo strato di copertura che supporta: quando tale equilibrio si rompe, la salute del suolo si deteriora causandone il degrado. Il contenuto di carbonio organico nel suolo (SOC) è stato proposto come indicatore per quantificarne lo stato di salute. Se il SOC è certamente molto importante per tale valutazione, tuttavia non dovrebbe essere considerato come indicatore complessivo per tutti gli aspetti della salute del suolo

Soil has drawn a large/substantial share of attention in land degradation studies compared to vegetation/biodiversity and water resources. Indeed, the original definition of the phenomenon of land degradation was described as the loss of soil productivity and also the GLASOD approach focused exclusively on soils. Although the status of soil depends on several factors, the concept of soil health has been proposed to provide a holistic indicator or index of the condition of the soil in a given

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situation. This soil health concept has been recently developed by the LADA[1] project implemented by FAO (Nachtergaele et al., 2011), and has been proposed as one of the impact indicators in the context of the UNCCD reporting process (Orr, 2011). In this regard, the status of soil health is derived from soil properties that are matched with the actual land use and management practices, so that the concept of soil health reflects the human-soil ecosystem interrelations which determine the soil condition and its dynamics.

However, given the difficulties linked to the assessment of a wide range of indicators of soil health, steps are being taken by several actors, including the GEF, to identify the soil organic carbon as the key single indicator of soil health. Soil is the main pool of organic carbon on Earth, hosting about 1500 Gt of OC, a quantity that is greater than the combined atmospheric and vegetation pools (Lal, 2004). Soil Organic Carbon (SOC) is also a fundamental determinant of fertility, contributing to the biological, chemical and physical aspects of the soil and its capability to sustain plant growth.

During the LADA project, a global study was carried out considering a number of characteristics of land and soil, chosen as indicators of the ecosystem services that land can provide. Some 34 global datasets have been used to collate the information needed to assess and map the indicators of land/ecosystem status and trends. Those indicators have been organized in six main aspects or determinants – biomass, soil, water, biodiversity, economic and social – and indexed in order to create a harmonized representation of the information. In conducting the assessment, both the actual status of the land and the degradation trend have been considered for each of the six aspects. The six aspects have been organized in a radar diagram with six axes to depict the summary result (Figure 1). This paper will focus only on the soil, hence considering only one of the six aspects or indexes of land condition.

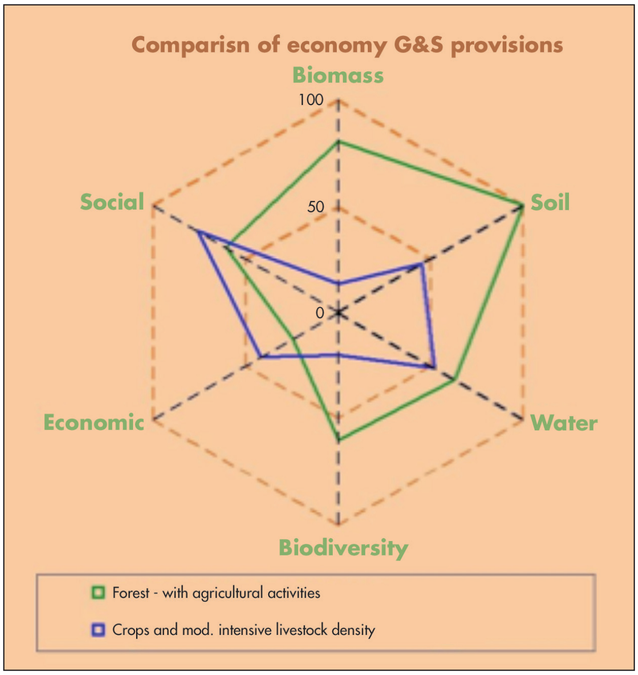

FIGURE 1 Radar diagram of land ecosystem services

Soil health status

The status of soil health has been assessed according to the capability of the soil to support the actual land use. So, it has been considered that a soil under natural vegetation tends to be in equilibrium with its cover, and can be consequently assumed to be in good health compared to a soil under human influence which may be degrading, stable or improving depending on the land use and management practices. Soils under agriculture have been classified on the basis of a management factor, calculated according to the Global Agro-ecological Zoning principles (GAEZ) and based on the ratio of actual yield compared with the Maximum Attainable Yield (the latter calculated on the basis of the status of natural resources). (Fischer et al., 2002). Soils under pastoralism have been classified according to the estimated amount of livestock. A preliminary map of the status of soil health is provided in Figure 2.

Soil Degradation Trends

The trend of soil degradation has been assessed by giving a qualitative evaluation to some degradation processes that have been identified as the most important variables that are at the same time possible to evaluate worldwide as global data currently exist. Physical and chemical processes have been considered separately. These

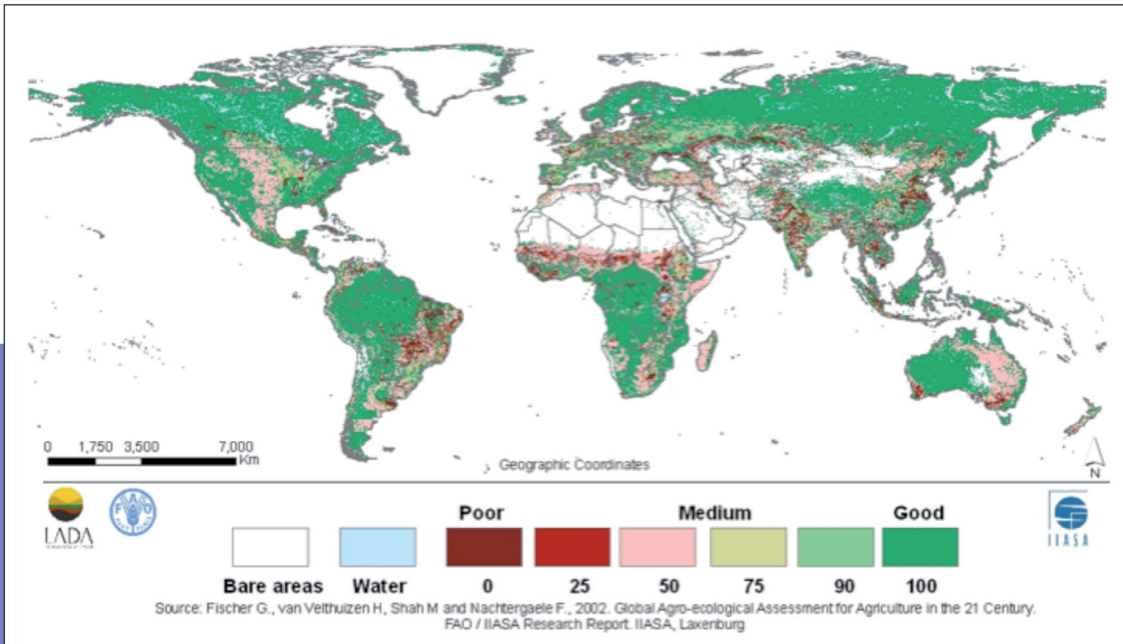

FIGURE 2 Soil health status for present land use

are influenced by soil biological processes, however, global data is not available on soil biodiversity and soil biological function.

Main Degradation Processes Affecting the Physical Characteristics of Soils

Several degradation processes affect the physical characteristics of the soil and its capability of providing ecosystem services. Three major aspects of the physical well being of soils are (a) sealing and crusting (b) erosion by both water and wind, and (c) compaction.

(1) **Soil sealing and crusting.** Soil sealing refers to the artificial covering of the soil surface so that it becomes impermeable to water. It is prevalent in cities and roads, and can be considered an entirely artificial condition. Soil crusting is another phenomenon at the surface of the soil, resulting from the impact of raindrops on the soil surface. It depends on soil texture, aggregate stability, topography and rainfall characteristics (Valentin et al, 2004, Gardner et al, 1999). Although crusting is due to natural processes, soil management factors influence the possibility of its formation in cultivated soils. Crusting reduces the infiltration rate of water, and constitutes an obstacle to the emergence of seedlings.

(2) **Soil erosion.** Erosion by water is probably the most well known and "popular" aspect of soil degradation, and the most researched one. In the case of water erosion, it may result in substantial loss of topsoil due to sheet or rill erosion or severe landscape deterioration by gullies and ravines, all contributing to sedimentation downstream and the silting up of dam reservoirs. Wind erosion is prevalent in exposed drylands and may result in substantial movements of soil across the landscape, resulting in sand deposits and mobile dunes that may smother arable lands and dust storms that deposit the finest particles even thousands of kilometres from the source. Not all effects of soil erosion are negative locally and they may indeed improve downstream soil fertility, as it is the case in the large rivers deltas that would not exist without erosion in the upland mountains. Nonetheless, accelerated wind and water erosion cause substantial degradation of farmland and loss of productivity on

sloping lands, and most of the displaced soil and nutrients end up in rivers or dams to be finally largely lost in the sea. Extensive research on soil erosion by water has been carried out and formulas exist allowing the prediction of the soil loss as a function of slope, soil type, rainfall, effective land cover and protecting practices (Wischmeier and Smith, 1978). On the contrary, wind erosion is much more difficult to estimate due to the lack of global base data.

(3) **Soil compaction** is mostly caused by high livestock densities in dry grassland areas that trample the soil and to mechanisation in agriculture, mainly due to repetitive hoeing and ploughing that results in a compacted layer or hard pan at hoe/plough depth and the traffic of heavy machinery for planting, harvesting and other operations. The effects on soil health are variable depending on soil moisture, texture and mineral composition, but they often result in the creation of impermeable soil layers at, or close to the surface – impeding infiltration and causing runoff and erosion – and in reduced porosity, both affecting water retention/availability to plants and preventing roots from penetrating the soil and, hence, plants to grow.

Main Degradation Processes Affecting the Chemical Properties of Soils

Soil health can also be damaged and degraded through chemical processes. Three major aspects of chemical soil degradation are soil nutrient mining, salinization and pollution.

(i) Soil Nutrient mining

Nutrient depletion of soils is a widespread soil degradation phenomenon that can occur as a consequence of soil erosion, since it is the topsoil, in which generally most soil nutrients are present, that is eroded first. One important additional cause are poor management practices such as slash and burn and other subsistence agricultural practices that do not replenish the nutrients taken out of the soil by the crops.

(ii) Soil pollution

Soil health is also affected by the presence and accumulation of toxic substances that may be associated with very high agricultural input and management levels. For instance cadmium toxicity is related to high phosphorus applications, while the use of excessive amounts of N-fertilizer or untimely applications in regard to rainfall, irrigation and the stage of the crop often leads to nitrate pollution of groundwater.

(iii) Soil salinization

Excess salinization occurs generally because of inadequately managed or maintained irrigation systems, particularly in arid and semi-arid areas. The inappropriate use of salty water and the tendency to cover a large area with limited quantity of available water are common causes of salinization. Indeed, in soils prone to salinization due to high evaporation rates and upward concentration of salts due to capillarity, large amounts of irrigation water are required to not only meet crop requirements but also leach out collected salts from the root zone.

Soil Improvement

Whilst poor land management practices are the main cause of soil degradation – due, for example, to soil disturbance, poor vegetative cover, decline in soil organic matter and nutrients, and so forth –, good management can improve the status of a degraded soil in terms of its bio-physical and chemical properties and functions. Sustainable Land Management practices that are appropriate for a given agro-ecological and socioeconomic context are instrumental in maintaining and improving soil health. Of particular importance in terms of soil ecosystem function and resilience is the management and conservation of the organic carbon content in croplands, grazing lands and forests.

Overall Soil Health Processes

The overall soil health degradation rating is derived by cumulative assessment of the above processes, which determine the extent and degree of soil degradation or soil improvement processes. The global results are given in Figure 3.

Land Degradation and Organic Carbon

Although in many cases soil degradation processes cause a decrease in the content of organic carbon in the soil (SOC), this is an aspect that cannot be generalized. In fact, while the physical processes described above may all create the conditions for a decrease in the SOC

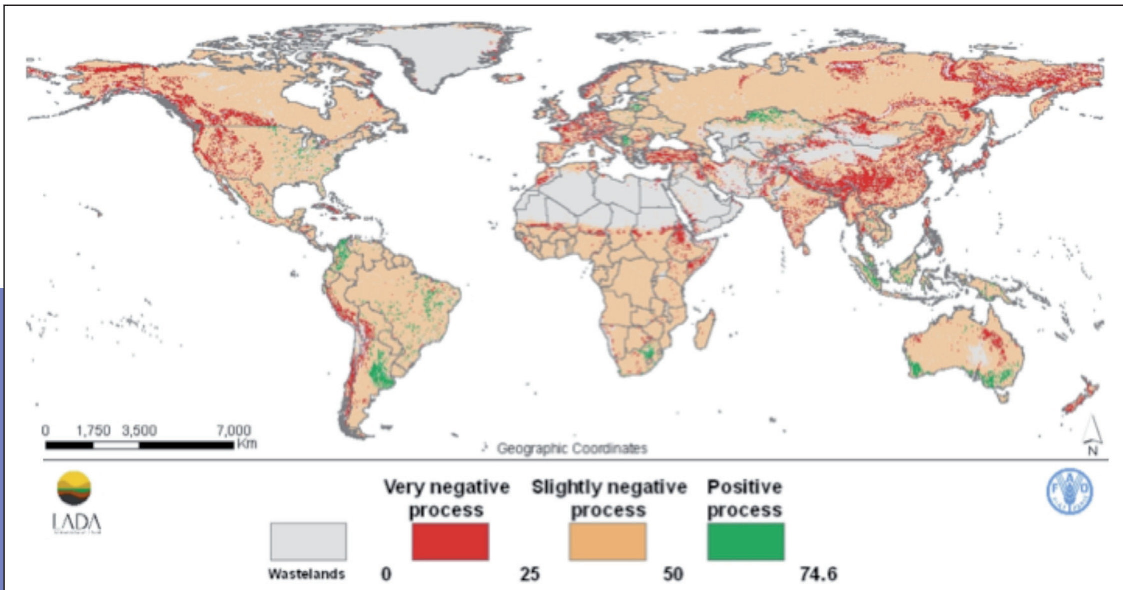

FIGURE 3 Soil health trend

content, chemical degradation can occur also in soils with a high SOC content.
Also, the amount of SOC cannot be used as an indicator for comparison among different types of soil. A healthy soil in a semi-arid environment may well have a lower SOC content than a degrading organic soil in a humid boreal environment. Hence, rather than the absolute content, two parameters should be considered: the change of SOC content over time and the difference between the actual SOC and the maximum possible SOC in the given conditions. While the former is a matter of measurement capacity at a given scale, of soil samples or proximal sensing (such as infrared spectroscopy), the latter has been the subject of the carbon gap study carried out by FAO in 2007. According to the study, "soil carbon gap" indicates situations where soil carbon levels are currently low but medium-to-high technical potential for sequestration exists, depending on soil type, climate, soil moisture and land cover conditions (FAO 2007). The same study reports that around 30 percent (4.7 million km^2) of the land characterized by medium-to-high potential for carbon sequestration is located in areas where agricultural production is practised, representing 15 percent of total croplands as defined by GLC 2000. Approximately one quarter of this area is located in Asia and one-quarter in Africa.
The utilization of the Soil Organic Carbon as an indicator or proxy for land degradation is appealing, but needs to be specified and contextualized.
First, the sole focus on SOC is not comprehensive in terms of health or condition of the soil. Pollution and salinization through human activities can occur in soils with high content of organic carbon. Soil organic matter is the food for soil organisms and determines both the soil biodiversity and the associated soil biological functions. Moreover, soil biological processes can break down soil contaminants. However, the relationships are not widely researched or understood and are very complex (type of contaminant, pedaphic and climatic factors, etc).
The soil organic carbon content depends on the rates of decomposition and replacement of the organic material, or in other words the soil carbon balance in terms of SOC sequestration and CO_2 emissions.
SOC content may also be affected by other degradation types, like erosion or compaction. The SOC content determines the availability of nutrients and the retention of soil moisture, which is also affected by the soil pH (chemical reaction), which is influenced by natural and human factors like, e.g., mineral composition, leaching by rainfall, fertilization).
Different soils have different levels of carbon, which cannot be easily changed as SOC can be added but this

is likely to then cause an increase in the soil biological activity and respiration of CO_2 . So, a map of the content of organic carbon could not be equalized to a map of soil degradation, and not even to a map of soil health. In fact, even if all soil on Earth would be in its pristine state, there would be still wide differences in its SOC content in different locations, under different climatic conditions and upon different bedrocks.

Even the change in SOC content cannot be considered as a final determination of the actual soil health status and degradation process. In fact, when a soil is already heavily depleted, and possibly under intensive agricultural use, its content in SOC may not diminish anymore. However, still it may be subject to physical degradation, like erosion or compaction, and it is actually more likely to degrade due to the loss of organic cements and the pulverization by livestock or farm machinery. SOC can be divided into fractions, with a stable fraction and labile fractions that are affected by management practices.

Measurement of soil organic carbon is more complex than it may appear, due to high levels of spatial variation, changes in SOC content with soil depth, and uncertainty of predictive models. Although, of course, there are well established laboratory techniques, the measurement of SOC in the field is far less precise, and would need the support of laboratory backup. At large scale, spectrographic technologies based on remote sensing and modelling using field sampling are being increasingly used and seem to provide rather reliable results for SOC. However, they tend to be used to reflect the situation in the top 30 cm or so of the soil profile. Until these measurements and models are more widely used and validated in the wide range of agro-ecological contexts, it may be difficult to use this important parameter of soil health as an indicator of land degradation or improvement at large scale, at the global or national level.

Conclusions

The concept of soil health is very useful to evaluate the capability of the soil to provide ecosystem services in relation to its present land use. Although soil degradation is a complex phenomenon, where many factors are involved, the need has been expressed by some international actors – and specifically by the GEF – of identifying one single indicator of the capability of soil to provide global environmental benefits. The content of organic carbon in the soil has been proposed as a measurable indicator to this end. However, a distinction needs to be made among different ES, in particular between production and regulatory services, when dealing with soil health assessment. In fact, while SOC can be a good indicator of the capability of soil in regulating the carbon cycle, it is a less specific indicator of productivity, as this depends heavily on other natural factors and management practices.

As often happens when dealing with land degradation assessment, the use of SOC as a single indicator will depend essentially on the ultimate purpose of the assessment itself, but it should not be considered as the overall indicator for all aspects of the degradation process.

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