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Soil indicators to assess the effectiveness of restoration strategies in dryland ecosystems

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Abstract

Soil indicators may be used for assessing both land suitability for restoration and the effectiveness of restoration strategies in restoring ecosystem functioning and services. In this review paper, several soil indicators, which can be used to assess the effectiveness of restoration strategies in dryland ecosystems at different spatial and temporal scales, are discussed. The selected indicators represent the different viewpoints of pedology, ecology, hydrology, and land management.

The recovery of soil capacity to provide ecosystem services is primarily obtained by increasing soil rooting depth and volume, and augmenting water accessibility for vegetation. Soil characteristics can be used either as indicators of suitability, that is, inherently slow-changing soil qualities, or as indicators for modifications, namely dynamic, thus “manageable” soil qualities. Soil organic matter forms, as well as biochemistry, micro- and meso-biology, are among the most utilized dynamic indicators. On broader territorial scales, the Landscape Function Analysis uses a functional approach, where the effectiveness of restoration strategies is assessed by combining the analysis of spatial pattern of vegetation with qualitative soil indicators. For more holistic and comprehensive projects, effective strategies to combat desertification should integrate soil indicators with biophysical and socio-economic evaluation and include participatory approaches. The integrated assessment protocol of Sustainable Land Management developed by the World Overview of Conservation Approaches and Technologies network is thoroughly discussed.

Two overall outcomes stem from the review: (i) the success of restoration projects relies on a proper understanding of their ecology, namely the relationships between soil, plants, hydrology, climate, and land management at different scales, which is particularly complex due to the heterogeneous pattern of ecosystems functioning in drylands, and (ii) the selection of the most suitable soil indicators follows a clear identification of the different and sometimes competing ecosystem services that the project is aimed at restoring.

1 Introduction

Restoring degraded drylands is a complex issue that can be pursued by means of several strategies, all of which consider soil characteristics, either directly or indirectly. If soil nature is of utmost importance in designing restoration strategies, soil dynamic properties can be used to monitor and assess the consequences of restoration activities on ecosystem functioning and services. Finding suitable indicators to monitor restoration activities at different scales, both within ecosystems and in the broader socio-economic system, requires: (i) a full understanding of soil–plant–ecosystem relationships, (ii) an interdisciplinary and integrative approach to restoration issues. The integration of different viewpoints from complementary disciplines is, nevertheless, still uncommon in restoration. Drylands' restoration, due to their idiosyncratic characteristics of high spatial heterogeneity and temporal variability, represents an even greater challenge, requiring restoration indicators able to reflect different spatial and temporal scales. The objective of this review is to present and discuss soil indicators showing potential to check the effectiveness of restoration activities in drylands at different spatial and temporal scales focusing on different ecosystem functions and by extension, to their services. The subject is treated from the viewpoints of specialists coming from different disciplines, namely pedology, ecology, hydrology, and land management, all dealing with the practice of ecosystems restoration. This paper is presented in three parts. The first part introduces linkages between land degradation, ecosystem services and restoration, stressing specificities of dryland ecosystems; the second part deals with soil indices and indicators to be used before and after restoration at different scales, and their relationship with soil processes and ecosystem services; the third part addresses more integrated assessment of restoration, linking ecological issues with socio-economic perception. To achieve these aims, several soil indicators and indices with potential to assess the effectiveness of restoration actions are selected, according to expert knowledge and a literature review.

Restoration of ecosystem services in drylands

Land degradation is related to the loss of ecosystem services and is referred to as desertification when it occurs in drylands. Desertification is considered a process leading to a final stage of land degradation, implying the loss of sustainable provisioning services such as agricultural and forestry production. This loss is irreversible, or has very little chance of reversibility in the referenced socio-economic conditions without external inputs ("functional sterility") (Costantini et al., 2009b).

A wide range of options are available for restoring the ecosystem services in degraded lands. Strategies intended to enhance ecosystem functions can be broadly classified as prevention, mitigation, and restoration interventions (Zucca et al., 2013a). The interventions carried out in agro-ecosystems are focused at improving livelihood by conserving or increasing biological and economic productivity. In these cases, terms such as sustainable land management (SLM), rehabilitation, and reclamation are commonly utilized for indicating increasing intervention intensities (Fig. 1).

The wide range of approaches and techniques forms a sequence of restoration options. Optimal choices must be context-adapted and depend on trade-off evaluation. Yet, while passive restoration activities could be effective under relatively moderate degraded conditions (e.g., removing disturbance factors), active approaches may be necessary in more heavily degraded or stressed environments. One of the passive restoration techniques, "inaction", that is, stopping grazing in over-grazed rangelands or leaving fallow intensively managed croplands, has proved to be effective over the long-term, although certain risks may threaten recovery, such as wildfires or the spread of invasive species. On the other hand, active restoration activities would require plant introduction with utilization of resources that are often limited, such as human labor, machinery, chemical products, tree planting, etc. Using vegetation is the most common approach in land restoration. By regulating a range of hydrologic, geomorphic, aeolian, pedogenetic, and biotic processes at the micro, patch, and hillslope scales, plants increase ecosystem health by their productivity and diversity. Due to limited water availability, the restoration of degraded drylands is more challenging than those under more humid environments. It is therefore reasonable that restoration efforts in drylands by planting would primarily work to increase rooting depth and soil volume, in order to increase the access to larger and more stable water supplies. However, restoration of degraded lands is more than the recovery of soil ability to support vegetation. In addition to biomass production, restoration strategies should target restoration of ecosystem processes (e.g. nutrient cycling, decomposition, etc.), increasing additional ecosystem services such as biodiversity, carbon stock increase, greenhouse gases reduction, flood and sediment regulation, and more (MEA, 2005).

2 Specificities of dryland ecosystems: vegetation structure and dynamic

Drylands are water-limited environments, where evaporative demands are not compensated by moisture inputs through precipitation and biomass production is constrained. In general, the lower the precipitation, the higher the bare soil occurrence between shrubs and herbaceous plants. Nonetheless, the relationships between precipitation rates and vegetation cover may not be linear (Hirota et al., 2011). The frequency of intermediate states between forest, grassland and savannahs is small, highlighting the occurrence of tipping points where ecosystems can shift from one physiognomic state to the other. The different vegetation physiognomies of drylands (e.g. shrublands, grasslands) have different demands of soil water and nutrients, and different soil depths at which roots uptake water.

Spatial heterogeneity is another important feature of drylands. In arid areas, plant spatial distribution is generally patchy and more influenced by local soil conditions and slope aspect than in humid areas (Príncipe et al., 2014). The spatial pattern of vegetation causes discontinuities in biomass production, affects soil fertility and interacts with trophic chains, including soil microorganisms and rate of decomposition. This spatial heterogeneity gives origin to the so-called “islands of fertility”, where soil and water resources, coupled with improved micro-climatic conditions, may facilitate the establishment of other plant species underneath the canopy of trees or shrubs.

Drylands are also characterized by a high seasonal and inter-annual climatic variability, resulting in a highly variable distribution of precipitation over time. This temporal variability, along with soil characteristics (e.g., soil water holding capacity), determine how much water is available to plants and for how long, influencing vegetation structure and cover. Disturbance dynamics, such as livestock management, shrub clearing, or deforestation also greatly affect plant cover and vegetation structure.

2.1 Soil–plant relationships critical for restoration

The success of vegetation establishment in restoration projects of degraded drylands largely depends on the extensive understanding of the relationships between soil characteristics and plant rooting features.

Globally, the soil depth at which different plant growth forms absorb water varies considerably (Canadell et al., 1996). In water-limited ecosystems, root systems' mean depths increase with above ground size: annuals < perennial forbs and grasses < dwarf-shrubs < shrubs < trees (Table 1, Fig. 2). Stem succulents are as shallowly rooted as annuals but have relatively high lateral root spreads (Schenk and Jackson, 2002a). Hence, soil properties that determine water availability along the soil profile largely determine the type of vegetation with potential for establishment.

For instance, savannah-like systems of holm oak (*Quercus ilex* L.) and cork oak (*Quercus suber* L.) woodlands, found in western Mediterranean Basin drylands, have a grassy understory dominated by annuals, with most of the roots concentrated in the upper 20–30 cm of the soil. In general, this upper layer includes organic soil horizons, where the overall root density is highest, most likely because it stores nutrients and has higher water-holding capacity. However, grassland areas are often intermingled with shrub patches, which evidently get water from deeper soil layers. Some of the most prominent shrubs in these systems are the shallow-rooting (30–40 cm) rockroses (Cistaceae family), which have a high lateral root spread. Such root systems may improve water-use efficiency. When soils are deeper, shallow rooted shrubs may coexist with deeper rooting plants such as the strawberry tree (*Arbutus unedo* L.) or the mastic tree (*Pistacia lentiscus* L.) that may get water lower than 2 m (Silva et al., 2002). Deep roots play a fundamental role during the dry season, because they reach deeper layers where water depletion is not as widespread as at the surface. In fact, the dominant oak trees in Mediterranean woodlands seem to get water from even deeper depths (groundwater), particularly during the dry season (Kurz-Besson et al., 2006).

Another example is the Ibero–North African dryland steppe, dominated by the perennial alpha grass (*Stipa tenacissima* L.). Its root system goes no further than 50 cm depth (Cortina et al., 2009), somewhat similar to the aforementioned shallow-rooting shrubs, enabling the species to access upper soil layers after small rainfall events. In these environments, biological soil crusts are a prominent feature covering bare soil. They play an important role by protecting soil surface from wind and water erosion, participating in nutrient cycling, reducing loss of water due to evaporation, and taking part in biotic interactions (e.g. influencing seed germination of vascular plants) (Bowker et al., 2014). Biological soil crusts have been introduced in deserts in several parts of the world in order to help prevent erosion and desertification (e.g., USA, China, Israel).

Soil heterogeneity is reflected in water distribution and availability for root uptake along the soil profile. The major factors affecting this distribution are soil particle size and seasonality of precipitation. Water-limited ecosystems tend to have deeper root systems in coarse-textured soils than in fine-textured soils, because the former have lower water-holding capacity and water tends to percolate more deeply, where groundwater, or a temporary perched water table, may be present. Conversely, the existence of a restrictive soil layer, for instance, in soils with a compacted or cemented layer, or high clay content in the subsoil, or showing shrink-swell properties (Vertisols), may favor shallow-rooted herbs, while limiting the establishment of deeper-rooted species, like perennial grasses or shrubs. Soil information concerning water availability of the different soil horizons, and not only of topsoil, is thus very important in order to adequately select the actions and species used to restore plant cover of degraded sites.

The residence time of water in soil, i.e., the period during which water remains available at a certain soil layer after a precipitation event, is particularly important for plant community in water limited ecosystems, especially during the growing season. The longer the period during which water is available, the greater the opportunity for plants to survive, grow and reproduce. For instance and in general, if water is retained in the uppermost soil layers, that may be beneficial for shallow-rooting herbaceous species germination and establishment. On the other hand, if water percolates rapidly to deeper layers, that may favor woody vegetation.

Precipitation distribution and seasonality, i.e., if precipitation is evenly distributed throughout the year or occurs during the cold or warm seasons of the year, plays a key role regarding water availability for plants along the soil profile. In drylands, shrubs are more shallowly rooted in climates with summer than winter precipitation regimes (Schenk and Jackson, 2002b). This is likely because in climates with summer precipitations, the residence time of water in the soil is shorter, and a wider and shallower root system is better able to uptake water before it evaporates. Good examples of this are succulent species, which are in general as shallowly rooted as annuals, but have denser lateral root systems, similar to shrubs. This life form becomes very widespread when low precipitation amounts are coupled with high temperatures, and hence water residence time is very short.

The assessment of water residence time in soils, and in particular, the information about when and for how long soil water is available to plants, is thus of major importance to predict the most suitable type of plant community for a given site.

3 The interaction between climatic aridity and soil characteristics: the soil aridity index

The aridity index (rainfall/evapotranspiration ratio, AI) has been taken by the United Nations Convention to Combat Desertification (UNCCD) as a reference for the definition of the areas subjected to desertification. The usefulness of the AI relies upon the relative ease it can be calculated from standard climatic data. However, the AI has several drawbacks. For example, it does not take into account the capacity of the soil to regulate water availability, deep drainage and runoff, which can vary noticeably inside the same climatic region. This is particularly true in transitional eco-zones, such as in the Mediterranean basin, where lands at high and low risk of desertification are very often finely intermingled (Costantini et al., 2009b).

Pedoclimate, that is soil moisture and temperature regimes, has also been used to characterize areas with a certain desertification risk (Eswaran and Reich, 1998). Actually, the American Soil Taxonomy considers soil moisture regime based on a yearly assessment of the number of days in which the soil moisture control section is either moist, partially dry, or completely dry, while soil temperature regime classification refers to mean annual temperature at 50 cm depth (Soil Survey Staff, 1999). Pedoclimate can be used as an indicator of inherent soil quality at different geographic scales. On a broader level, soil moisture and temperature regimes are used to delineate the areas at potential risk of desertification. In particular, the aridic, xeric, dry xeric and ustic soil moisture regimes refer to areas with varying degrees of potential water deficit, while soils with thermic and hyperthermic temperature regimes refer to lands with high temperatures in the root zone. At a more detailed level, the soil aridity index (SAI) was calculated as the average cumulative days per year when the soil moisture control section was completely dry (number of days with dry soil) (Costantini et al., 2009a). The SAI was specifically aimed at highlighting the differences in pedoclimate that may result from the rather detailed combinations of shallow soils, or with limited available water capacity. This value was estimated using software based on the Erosion/Production Index Calculation (EPIC) model. SAI was related to easily available climatic and soil data through a multiple regression, linking the SAI value to long-term mean annual air temperature, total annual rainfall, and soil available water content. The SAI showed a reasonable correlation with the AI and with the vegetation vigour and soil cover classes of natural and natural-like areas. In addition, the SAI highlighted a more consistent correlation with the Normalized Difference Vegetation Index (NDVI) class distribution than the AI (Costantini et al., 2009b). Being influenced by both soil and climate variations, SAI is particularly useful in highlighting vulnerable lands where increased rainfall deficit and enhanced soil erosion could lead to desertification. However, the use of the SAI at scales finer than national and regional should be improved by adding the influence of local morphology on runoff and subsurface water flows.

4 Soil indicators

Soil ecosystem services are determined by soil properties and their assessment requires the use of selected indicators (Calzolari et al., 2016). A wide range of soil indicators may be used, depending on the purpose and scale of evaluation. In restoration planning, soil indicators are needed to support both the design and monitoring phases. However, different information is needed for these two purposes. The design phase mainly requires information about soil (and site) attributes that may affect the probability of success of the intervention. The input properties used to work the indicators can be both inherent characteristics (De la Rosa and Sobral, 2008) such as topographic slope angle and aspect, surface rockiness, soil depth, texture, stoniness, structure, presence of subsoil pans, and subsoil wetness conditions, or more dynamic attributes such as acidity and salinity. Planning can be supported by the identification of “optimal” ranges of values of such variables that increase chances of success of restoration and/or decrease risks and costs, and this can be done by means of land suitability schemes. Several approaches are available to create indicators, ranging from traditional categorical or parametric schemes (Giordano, 2009) to more complex approaches integrating multicriteria analysis and decision support frameworks (Yi and Wang, 2013; Uribe et al., 2014).

The soil information needed to monitor and assess restoration depends on the time and spatial scales. In the short term, it might be important to focus on dynamic properties such as soil organic matter, pH, available phosphorus, nitrogen and other nutrients, macroporosity, etc. However, because of the large spatial and temporal variability of ecosystems, particularly in drylands, it is critical that indicators focus on “slow variables” (Carpenter and Turner, 2000) so that the assessment of long-term changes and of the sustainability of land management is not confused by short-term variations in land and socio-economic conditions (Zucca et al., 2013a). Slow indicators can more directly reflect impacts on inherent soil qualities, e.g., through improved structure and porosity and increased topsoil depth and water holding capacity. Table 2 shows a list of the most frequently used soil indicators, specifying their functional relevance.

4.1 Physical and hydrological soil indicators

In drylands, the most important soil indicators refer to the factors regulating water availability, which by itself, directly or indirectly depends on several morphological and physical soil properties, as well as on physiographic and land-use factors (Table 3).

A number of physical and hydrological soil indicators are available in order to assess efficiency of restoration activities such as sustainable land management (SLM) practices. Analyzing the SLM practices documented in the World Overview of Conservation Approaches and Technologies database (WOCAT, 2015) regarding these impacts confirms that water is the most common limiting factor for the provisioning service in drylands (Fig. 3). Improving soil moisture through in-situ conservation of rainwater or irrigation water often result in increased ecosystem services like production of food, fodder, fiber or fuel. Yet, runoff control is also important not only for increasing water availability but also for decreasing erosional processes and restoring the water cycle and regulation (e.g., flood control).

Rainfall and water availability are the crucial threat in drylands due to scarcity and variability, thus, improving water use efficiency is of utmost importance. The concept of Green Water Use Efficiency (GWUE), expressed as the fraction of plant transpiration over precipitation (Stroosnijder, 2009), provides a useful indicator in order to evaluate whether the productive water is maximized, while unproductive loss is minimized. Analyses of 30 SLM practices in drylands have revealed that half of these practices produce measurable improvements regarding GWUE (Fig. 4). Detailed knowledge about soil hydrology and hydrological processes allows quantifying the effect of land management on blue and green water distribution. The concept of blue and green water aims at shifting non-productive evaporation towards productive transpiration to improve biomass production without reducing the amount of blue water leaving a watershed. Reducing direct soil evaporation and thereby forcing it to be transpired through the plants is thus one of the key ideas behind turning blue water into green water. Better utilization of rainfall to capitalize on green water requires appropriate land and crop management systems, which can improve water-use efficiency. These can be evaluated again with the GWUE indicator as described above. Many indicators are difficult to measure and thus visual soil indicators are often used instead. These methods include the visual soil assessment (VSA), the visual evaluation of soil structure (VESS), the visual assessment of aggregate stability and more. A recent study by Moncada et al. (2014) demonstrated that visual examinations are reliable semi-quantitative methods to assess soil structural quality and can be considered as visual predictors of soil physical properties (Moncada et al., 2014).

4.2 Chemical soil indicators

Several chemical soil properties may affect and be affected by restoration interventions. The inherent soil fertility is linked to the capacity of the soil to retain and exchange nutrients, a measure of which is the cation exchange capacity (CEC). The CEC is directly related to soil mineral composition, particularly clay content and type, and the soil organic matter content. By increasing the latter, restoration interventions can have a direct impact on soil fertility.

Soil pH has an important role in restoration planning, as many plants used for restoration purposes have ranges of pH tolerance. For this reason, soil acidity is generally included in land suitability schemes for either farming or forestry. On the other hand, reducing excessive soil acidity can be a restoration goal. Restoration of acidic soils is an issue also in drylands, where natural acidic soils can be widespread as results of long-term pedogenesis and leaching, or localized, for example, as coastal and inland acid sulfate soils. High acidity is often found in contaminated soils of mining sites, where pH values can be very low. Restoration of such sites can be challenging and amendment of soils (e.g., liming) may be needed before plantation in order to reduce the availability of heavy metals and, hence, phytotoxicity to target plants.

Soil alkalinity and salinity are common in degraded drylands, particularly in irrigated lands degraded by inappropriate irrigation practices. Halophyte plants have been successfully used for restoring natural vegetation and/or recovering agricultural productivity in degraded saline and alkaline soils, and also for remediating these soils by actively extracting salt (Hasanuzzaman et al., 2014). On the other hand (Zucca et al., 2015a), contrasting effects were observed in sites located in arid central Morocco where halophyte shrubs (*Atriplex nummularia* Lindl.) were used to rehabilitate pastures. In this case, besides increasing soil organic matter and water infiltration, the plants have consistently increased the topsoil alkalinity (measured as SAR, or sodium adsorption ratio), showing that possible trade-offs have to be considered. Other restoration practices that imply the application of organic matter such as manures or biosolids might increase soil electric conductivity and affect seedling survival during severe drought years (Fuentes et al., 2010), although this effect also depends on the target species (Oliveira et al., 2011).

4.3 Soil organic matter

Soil organic matter and its functional fractions

Among the several factors of the soil capacity to provide ecosystem services, soil organic matter (SOM) is considered one of the most important. The main source of SOM is the above- and below-ground residues of vegetation. The humification and decomposition of these organic materials sustains the soil food chain, as the SOM gets utilized as a source of energy for the soil micro- and meso-fauna and fungi. At the same time, mineralization of the plant residues releases nutrients to the soil solution, where they become accessible for uptake by the vegetation's root system.

SOM has a complex nature and the different forms which result from the humification and decomposition processes have varying residence time in soil (Marschner et al., 2008). However, recent analytical and experimental advances have demonstrated that SOM molecular structure has only a secondary role in controlling its stability, which instead mainly depends on the biotic and abiotic environment (Schmidt et al., 2011). Actually, soil organic matter is subjected to microbial degradation and its persistence can vary depending on both chemical recalcitrance and physical protection. The discrepancy between chemical recalcitrance and residence time can be explained through physical protection mechanisms and physical disconnection between soil organic matter and microorganisms. Physical protection mechanisms can occur at particle-size and aggregate-size level through OC sorption on clay particles, as well as inclusion into micro-aggregates.

In drylands, the production of biomass, which constitutes the SOM source, is limited by water availability. In general, the size of SOM pools in natural ecosystems decreases exponentially with temperature (Lal, 2004). Consequently most drylands contain $\sim 1\,\%$ of SOM, and frequently less than 0.5 % SOM. At the same time, the smaller moisture content of soil controls decomposition rates, increasing the SOM residence time in drylands. SOM has an important role in determining the soil physical quality, and therefore, regulating the availability of water for vegetation. It impacts soil structure formation, particularly through its positive effects on macroporosity, and macro-aggregates formation and stability. As such, SOM regulates soil water infiltration and retention capacity. Besides regulating water availability, SOM also controls a range of ecosystem services.

In degraded drylands, where plant cover has been disrupted, the input of organic residues into the soil is considerably reduced. Furthermore, the susceptibility of degraded drylands to accelerated erosional processes becomes exacerbated, increasing the leakage of organic material and nutrients from the affected ecosystems. When considering restoration measures for drylands, the replenishment of soil organic carbon (SOC) pools should be considered as a specific goal. In such environments, where topsoil is thin and poor in organic matter, and highly susceptible to erosion, special attention should be paid to the specific restoration of this uppermost soil layer. Yet, standardized methodologies for assessing the state of SOC depletion are still missing. Besides the on-site and direct agronomic effects of SOC in terms of soil quality and productive capacity, the importance of SOC also stems from its indirect impact on surface processes. Low inputs of fresh organic matter would lead to slow macro-aggregation rate, reduced macro-aggregate stability, and decreased infiltration capacity of water. Regardless, besides the overall SOC concentrations and pools, the SOC composition is also important, as it affects its persistence in soil (SOC sequestration) on the one hand, and its availability for decomposition by microbial activity, which determine the soil fertility, on the other hand.

SOC is composed of different functional fractions, which are defined according to their persistence capacity (vs. decomposability). The three main groups are: (1) the transient fraction, which encompasses the easiest decomposable fraction, such as polysaccharides, with a turnover rate of weeks to months; (2) the temporary fraction, which comprises fine roots and fungal hyphae that are vulnerable to land-use and management; and (3) the persistent fraction, which includes the most resistant part of SOC, such as humified organic materials. These materials tend to get associated with amorphous iron, aluminum, and aluminosilicates, binding soil particles into micro-aggregates through clay–polyvalent metal–organic matter complexes, which can last for very long periods of time.

Of the above mentioned SOC functional fractions, the transient or “active” fraction, which is the most labile organic carbon (LOC) fraction, encompasses only very few percent of the overall SOC pool. Yet, since the LOC is the most responsive to land-use change and management practices (Fig. 5), it should be considered as a useful indicator of the overall status of soils. Moreover, the measurement of both LOC and total SOC enables to determine the carbon lability (L), which indicates the ratio between LOC and non-LOC organic carbon (Blair et al., 1995). L is determined by the equation:

$$L = (\mathrm{LOC})/(\mathrm{total\ SOC\text{-}LOC})\ [\%/\%]. \tag{1}$$

Three carbon-management related indices can be utilized for monitoring the impact of land-use change and management practices on the SOC pool. The first is the carbon pool index (CPI), which indicates the effect of land-use change or management practice on aggradation or degradation of the total SOC, and calculated according to the equation:

$$\mathrm{CPI} = (\text{total SOC in treatment soil})/(\text{total SOC in reference soil}). \tag{2}$$

The second is the lability index (LI), which indicates the ratio between carbon lability in the treatment soil and carbon lability in the reference soil:

$$\mathrm{LI} = (L \text{ in treatment soil})/(L \text{ in reference soil}). \tag{3}$$

The third is the carbon management index (CMI), which predicts changes in sequestration and lability of SOC as a result of changes in agricultural practices:

$$\mathrm{CMI} = \mathrm{CPI} \times \mathrm{LI}. \tag{4}$$

An additional advantage of the SOC-management related indices stems from their standardized (normalized) nature, easing the comparisons among different soils, ecosystems, and biomes, and their ranking according to the state along the degradation-restoration continuum.

Besides concentrations, pools, and composition, another important determinant of SOC is its stratification throughout the soil profile (Franzluebbers, 2002a). Stratification ratio of SOC is calculated by the SOC concentration in a shallow depth divided by this in a deeper depth. Overall, in undisturbed soils, a clear stratification occurs, with larger SOC concentrations in shallower than that in deeper layers. In disturbed soils, the SOC stratification becomes blurred (Fig. 5). Therefore, if comparing the same soil type, in the same climatic region and biome, and in the same geomorphic unit, the clear stratification of SOC would indicate an undisturbed soil profile, while lesser stratified SOC would indicate a certain rate of land degradation. It was suggested that the greater stratification ratio in natural lands stems from the combined effect of accumulation of organic materials on the ground surface, coupled with the undisturbed soil profile. Furthermore, in addition to the stratification ratio of the total SOC, the stratification of active SOC fractions seems to be more sensitive to degradation than that of the total SOC (Franzluebbers, 2002b). Therefore, the SOC stratification ratio can be considered as a valuable indicator of both the biological and hydrological functioning of soil. The SOC stratification ratio easily allows the comparison of different soils, since it normalizes SOC into a unitless value and overcomes the inherited soil characteristics.

4.4 Soil biochemical and microbiological indicators

It is well known that the size, composition and activity of the soil microbial communities may indicate the possible success of restoration of degraded lands, and the impact of management strategies upon them (Harris, 2003). Biological indicators have been widely used to monitor soil quality changes in space and time and to assess biological fertility (Marinari et al., 2010). Most used indicators include microbial biomass carbon, microbial respiration, enzyme activities, and related indices (Table 4) (Kieft et al., 1998; Bastida et al., 2006). Tentative classes of indicators have also been suggested to simplify the estimation of soil biological stress (Benedetti and Mocali, 2008) (Table 5).

In general, a number of selected microbiological indicators are already available for assessing soil functioning (Bloem et al., 2005) which are usually divided into three essential groups, depending on the information they provide: (1) Soil microbial biomass and number, (2) Soil microbial activity, (3) Soil microbial diversity and community structure.

Group (1). Several conventional methods capable of determining weight and number of soil microorganisms are based on direct or indirect procedures (Alef and Nannipieri, 1995). The assessment of the total size of the viable microbial community requires culturable cells and comprises the plate count and the most probable number (MPN) techniques. However, about 99 % of soil microorganisms are unculturable (Torsvik et al., 1990). Therefore, biochemical and physiological methods, e.g., chloroform fumigation extraction (Vance et al., 1987) and substrate-induced respiration (SIR) are the most commonly used.

Group (2). The metabolic turnover of the microbial biomass and the conversion of nutrient pools are usually assessed as *potential* activity, as to date, no serial and routine methods are available for open field measurements. Potential activity means metabolic activity, including enzymatic activities that soil microbes are capable of developing under optimal conditions in the laboratory. As previously reported, SOM decomposition is carried out by microorganisms through the enzymatic attack of SOM and microbial respiration: in fact, extracellular enzymes degrade SOM through hydrolytic or oxidative processes, producing assimilable dissolved OM that can be rapidly incorporated by microbes. It is known that when substrate availability and enzyme activity do not constrain reaction rates, decomposition rates increase with temperature. Biologically-active forms of SOM can function as short-term indicators of longer-term changes in SOM.

Group (3). Currently, a number of methods are available for the assessment of soil microbial diversity. The use of molecular techniques for investigating microbial diversity of soil communities continues to provide new understanding of soil properties and quality. The analysis of the soil-extracted nucleic acid sequences (DNA and RNA) provides a powerful tool for the characterization of the entire microbial community. Among the most useful and commonly used methods are those in which small subunit RNA genes are amplified via Polymerase Chain Reaction (PCR) and analyzed by means of several fingerprinting techniques such as Denaturing Gradient Gel Electrophoresis (DGGE), Terminal Restriction Fragment Length Polymorphysm (T-RFLP) or single-strand conformational polymorphism (SSCP) (Kowalchuk, 2004). Recently, various omics approaches are rapidly advancing in soil science, although they are not ready for widespread adaptation yet (Myrold and Nannipieri, 2014). Nevertheless, among omics, the metagenomic approach is one of the most promising to simultaneously assess both soil microbial diversity and function (Benedetti and Mocali, 2010).

The analysis of types and amounts of different phospholipid fatty acids (PLFA) is a biochemical approach that offers an alternative to molecular techniques, since it reflects both microbial taxonomic and functional diversity. The amount of total PLFA can be used as an indicator for viable microbial biomass; a further characterization can be done based on specific signature of biomarker fatty acids. Unfortunately, this technique does not include Archea organisms, since their cell membrane contains ether-linked rather than ester-linked phospholipid fatty acids (Pennanen, 2001). Functional and metabolic features of soil microbial communities have been also analyzed through the assessment of the Community-level-physiological profile (CLPP) using Biolog plates (Pignataro et al., 2012).

The future challenges will be addressed towards standardizing some methodologies, in order to provide quick, reliable and inexpensive information. All the *omics*, in particular, have the potential to provide comprehensive and complementary information to traditional techniques, and help monitoring changes in soil functions at the very detailed spatial and temporal scales.

4.5 Soil mesofauna

Beyond the approaches to soil quality evaluation based on the use of physical, chemical and microbiological indicators, new methods, based on soil mesofauna composition (microarthropods < 2 mm), have been proposed for the evaluation of soil ecosystem services, in particular, biodiversity pools. In fact, soil-dwelling animals have a significant role in the colonization and in the restoration of degraded biological habitats (Starý, 2002); their role includes litter fragmentation, soil aggregation and porosity formation, water infiltration and distribution of organic matter in soil horizons (Bird et al., 2004). According to Dickinson et al. (2005), soil biodiversity is probably the most important factor for maintaining ecosystem function in disturbed environments. The higher the number of mesofauna different groups adapted to the soil habitat, the better the soil functionality. Actually, healthy soil systems show a set of ecosystem niches and related organisms, while stressed soils are poorer, both in species and individuals (Menta et al., 2011). Mesofauna responds to land-use and management practices and can be considered an efficient bio-indicator of ecosystem health.

Yet, one of the main problems related to the bioindices remains in the difficulty in classifying organisms at the species level. For this reason, an approach based on the types of edaphic microarthropods, the QBS-ar index, has been developed (Parisi et al., 2005). It overcomes difficulties linked to the identification at species level, by focusing on the evaluation of the adaptability to the hypogeal life (Madej et al., 2011). The method itself is rather simple and easy: a soil sample is put in a Berlese–Tullgren extractor to collect organisms, which are then observed under a stereomicroscope and identified at the taxonomic level requested by the index. According to the species adaptation to soil environment, a score from 1 to 20 (eco-morphological index, EMI) is assigned. The QBS-ar index results from the sum of these scores. Higher values correspond to more complex and soil-adapted communities (Mazza et al., 2011). QBS-ar has been applied on a range of soil types and land uses and its validity was evaluated for assessing soil biodiversity in different settings.

5 Functional approaches in the monitoring of dryland ecosystems: the Landscape Function Analysis

Most commonly, mitigation and restoration actions are evaluated based on vegetation cover and composition. However, functional approaches that also account for the spatial pattern of vegetation seem to be more suited to the assessment of soil ecosystem functioning. As previously highlighted, many drylands around the world present a patchy distribution of vegetation following a sink-source spatial pattern. Source areas have a negative balance of resources that accumulate in the sink areas. Beyond this redistribution of resources at the detailed scale, a fully functional ecosystem includes the retention within the system. In dry ecosystems, vegetation patchiness can provide a measure of the landscape capacity to conserve water and nutrients (Cerdà, 1997). The assessment of the functionality of these ecosystems should include the description of the spatial distribution of vegetation (size and connectivity of different plant type patches) in combination with soil properties that determine the conservation of resources, especially regarding soil surface attributes. Landscape Function Analysis (LFA) (Tonway and Hindley, 2004) incorporates both approaches in the evaluation of dryland patchy ecosystems, using functional indicators instead of direct measures of key processes which are expensive to implement. This method assigns a prominent role to the soil surface condition. The LFA uses semi-quantitative field-based indicators (Table 6) to evaluate soil surface condition at the hillslope scale in every identified type of patches and interpatches, targeting surface properties that control stability, nutrient cycling and infiltration processes. The stability index provides an idea of the vulnerability to erosion and the ability to recover after stresses, the infiltration/runoff index indicates the ratio of rainfall water available to plants and export by runoff, and the nutrient cycling index indicates the in situ recycling of organic matter. For every single type of patch or interpatch, the scores of the quantitative indicators that have an impact on a particular index are summed up and referred to the maximum possible score. The final value of the index is calculated by weighing the attained values in all patch and interpatch types by its representativity in the working area.

Maestre and Puche (2009) observed significant relationships of the indices calculated through LFA with measured soil variables in alpha-grass steppes in southeast Spain. These authors found that the infiltration index was positively related to soil water holding capacity and negatively to soil compaction, and the nutrient cycling and stability indices were positively related to soil-nutrient variables and microbial activity. However, the sensitivity of the indices might vary depending on the scale and the contrast between different situations. This assessment represents an inexpensive, rapid, accurate and repeatable methodology for the evaluation of soil functioning properties, especially in patchy drylands. It is especially useful as a relative indicator when areas of contrasted histories and disturbance regimes of a similar ecosystem are compared. It has been used, for instance, to monitor the impacts on ecosystem functioning of restoration actions using exotic plant species (Derbel et al., 2009) or fodder shrubs and also to monitor the effects of grazing and reforestations (Zucca et al., 2013b). LFA infiltration and nutrient cycling indexes have been observed to relate significantly to perennial species richness in Mediterranean drylands (Maestre and Cortina, 2004). In addition, some of the LFA indices, especially infiltration and nutrient cycling, show good correlations with remote sensing indices such as NDVI (Gaitán et al., 2013). The combination of these two approaches at such different scales may provide useful information on ecosystem functioning and might be a good tool for dryland management by selecting and prioritizing areas to restore.

6 Integrated assessment protocols

Integrated assessment protocols combine field observations of key ecosystem attributes, socio-economic surveys, and remote sensing (RS) based geospatial information. Particularly, to conduct the evaluation over wider areas, RS should be employed for land cover change and ecosystems' natural temporal pattern detection, land degradation assessment, and analysis of the impacts of land restoration (Zucca et al., 2015b; Ramos et al., 2015). The quantification of the photosynthetically active herbaceous and shrub biomass production in rangelands and savannahs is one of the most widely used metrics.

In order to more holistically assess the impacts of management and restoration measures, i.e., to identify their ecological, economic and socio-cultural effects, both over the short- and long-term as well as on- and off-site, more comprehensive methods are needed. The WOCAT network (www.wocat.net) has developed such methods in order to document and evaluate SLM technologies and approaches applied in the field. The methods are internationally standardized and since 2014, are accredited by the UNCCD as their documentation and knowledge sharing platform. The role of science in monitoring and assessing desertification, as well as mitigation/restoration actions, is to produce evidence of their impacts on natural resources and to assess the implications of these impacts on local societies. However, sophisticated and detailed assessment is often expensive and time-consuming and depends on the availability of skilled experts. On the other hand, stakeholder engagement in assessment of indicators is still rare or limited in scope. In order to evaluate mitigation/restoration practices, performance indicators – e.g., the impact of a given practice on degradation and its economic, ecological, and socio-cultural benefits or disadvantages – should be assessed. These are mostly not available quantitatively, but can only be assessed qualitatively by experts, ideally according to predefined response categories (such as "no/negligible" for 0–5 %, "little" for 5–20 %, "medium" for 20–50 %, and "high" for > 50 % of change) in order to ensure comparability over practices, sites and time. However, where available, quantitative data should be included as well (Schwilch et al., 2011, 2014). Soil and vegetation related indicators used in the WOCAT SLM technology questionnaire and assessed in the above described way include soil moisture, evaporation, surface runoff, soil cover, biomass/above-ground C, nutrient cycling, soil organic matter, soil loss, plant diversity, invasive species, beneficial species, etc. Another important aspect is the evaluation of the technical function, such as whether the practice works though an improvement of ground cover, surface roughness, soil structure, water availability, vegetation varieties, etc.

Based on such assessments, conclusions can be drawn as to whether and how the documented practices address key threats in drylands, i.e., by means of improved water management, reduced soil degradation, diversified and enhanced production, resilience towards climate change and variability, and by providing socio-cultural benefits including conflict mitigation and prevention of outmigration. Such a thorough impact assessment is mandatory in order to justify investments in more sustainable land management. However, these investments are often beyond the means, responsibility and decision-making power of individual land users and thus an effective collaboration and partnerships among stakeholders at all levels is required. Engaging stakeholders throughout the environmental assessment process can result in the integration of local people and their perceptions into management, planning and evaluation, helping develop feelings of ownership (Reed et al., 2007). Bringing the scientist's up-to-date ecological and technical expertise together with the land users' experience, can only be achieved through true and effective collaboration between stakeholders. It is thus generally acknowledged that mitigating desertification requires multi-stakeholder dialogues and collaboration (Thomas et al., 2012).

7 Conclusions

The development of methods for assessing the success of the actions to combat desertification is considered as a priority by the scientific community. The "land degradation neutrality" target promoted by the UNCCD indicates that the progress made with restoration could compensate the impacts of degradation, stressing the importance of a quantitative evaluation process.

The failure of restoration plans is often caused by the choice of plants or practices that are not suited to the site. The success of restoration plans instead relies on a proper and detailed knowledge of the relationships between soil and plant properties and ecology in drylands and, in particular, on the assessment of the amount and timeframe of effective soil water availability. One of the main challenges is to select the different species to be used for restoration which have a pattern of the root system matching the horizon characteristics of the soil profile, as well as the specific climate and hydrology of the site. Dryland restoration is a site-specific activity, which implies considering soil spatial and temporal heterogeneity before plant placement.

The understanding of dryland ecosystem services stems from the very detailed scale of soil observation and analysis. A number of soil indicators support the design of measures and the assessment/monitoring phases. Such soil indicators need to refer to soil properties, which can actually be modified through management or restoration activities. Soil organic matter, in particular, is at the same time a key attribute for many ecosystem functions and one of the main factors affecting water availability. Soil dynamic properties related to the forms of organic matter, as well as biochemistry, micro and meso biology, are very sensitive to restoration activities. Although the functional forms of soil organic matter and related biological activities and organisms are still not completely understood and characterized, they are promising candidate indicators that may be utilized to assess the effectiveness of restoration strategies in dryland ecosystems.

A recent approach in assessing the effectiveness of restoration strategies in dryland ecosystems is combining the analysis of spatial pattern of vegetation with qualitative soil surface indicators. This simplified but effective methodology, specifically tailored for the surface patterns of drylands, allows the monitoring of landscape functioning variations in space and time, and it is particularly suitable for the assessments carried out at the intermediate territorial scales. On broader scales, effective strategies to combat desertification should be based on integrated biophysical and socio-economic evaluation methods. Evaluation and monitoring of progress and success are expected to demonstrate the benefits of sustainable management, establish cost-effective thresholds for intervention alternatives, and identify priority areas for action. Recent approaches propose to assess and evaluate the effectiveness of management and restoration programs based on indicators that relate to ecosystem integrity and services, as well as socio-economic and cultural variables related to human well-being, both over the short- and long-term, as well as on- and off-site. To this aim, there is a need for interaction and dialog among the diverse set of scientists and stakeholders involved, which can result in a co-production of new knowledge and at the same time in the formulation of new knowledge needs.

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Table 1. Absolute root dimensions (geometric means) for maximum rooting depths and lateral root spreads for seven plant growth forms in water-limited ecosystems worldwide. Geometric means marked by different letters are significantly different at $p < 0.05$ according to one-way ANOVAs (adapted from Schenk and Jackson, 2002).

	Rooting depths (m)			Lateral root spreads (m)		
	n	Geometric mean	95 % Confidence interval for geometric mean	*n*	Geometric mean	95 % Confidence interval for geometric mean
Trees	76	3.27 a	2.54–4.08	40	7.67 a	5.11–9.88
Shrubs	156	2.14 b	1.87–2.42	119	2.20 b	1.79–2.65
Dwarf-shrubs	305	1.27 c	1.16–1.38	227	0.64 c	0.56–0.72
Perenn. grasses	271	1.04 d	0.96–1.12	168	0.34 d	0.30–0.38
Perenn. forbs	330	1.05 d	0.95–1.15	270	0.30 d	0.27–0.34
Annuals	123	0.38 e	0.32–0.46	109	0.12 e	0.09–0.14
Succulents	43	0.28 e	0.21–0.35	32	1.37 b	0.84–2.02

Table 2. Example of soil quality indicators used in restoration.

Soil indicator category	Soil indicator	Relevance to soil processes and functions	Contribution to ecosystem services
Physical	Bulk density	Plant root penetration, porosity, gas exchanges	Biomass production, nutrient cycling, climate regulation
	Infiltration capacity	Runoff/erosion control, leaching	Soil development/conservation, water purification and regulation, flood mitigation
	Water holding capacity	Retention and transport of water and chemicals	Water purification and regulation, food and fiber production, biomass production
	Topsoil-depth	Rooting volume, habitat for soil fauna	Carbon sequestration, climate regulation, biomass production
	Macro-aggregation, soil structure	erodibility, nutrient and organic matter retention, crop emergence	Soil development/conservation, carbon sequestration, biomass production
	Surface stoniness	Infiltration rate and effective rootable soil	Soil development/conservation, water regulation
Chemical	Organic matter	Soil fertility and soil structure, pesticide and water retention	Carbon sequestration, soil development/conservation, nutrient cycling, water purification and regulation, biomass production
	Total nitrogen	Plant and soil fauna development	biomass production
	pH	Nutrient availability, pesticide absorption and mobility	Nutrient cycling, biomass production
	Cation exchange capacity (CEC)	Plant growth, soil structure, water infiltration	Nutrient cycling, food and fiber production, primary production
	Electrical conductivity	Soil water potential, salinity	Water purification and regulation, food and fiber production, primary production
Biological	Soil respiration	Biological activity, biomass activity	Nutrient cycling, water purification and regulation, pollutants purification
	Dehydrogenase activity and Phosphatase	Decomposition rates of plant residues release of plant-available nutrients	Nutrient cycling, food and fiber production, biomass production
	QBS	Mesofauna abundance and adaptation to the soil habitat	Biodiversity pool

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Table 3. Soil qualities related to water availability.

	Drivers	Soil qualities	Functional soil characteristics
Water input	Rainfall, Irrigation	Infiltration capacity	Infiltration rate (texture, structure, stoniness, cracks)
	Groundwater	Deep recharge	Capillary rise (texture, structure, stoniness)
	Surface and subsurface flows	Surface recharge	Topography, natural and artificial channels, ditches
Water output	Evapotranspiration	Surface cover	Mulch, stoniness, crusts
	Runoff	Surface morphology	Slope, mulch, stoniness, rockiness, crusts, micro relief, natural, artificial channels, ditches
	Drainage (rock nature, artificial piping)	Permeability	Hydraulic conductivity
Water storage	Soil volume	Porosity	Texture, structure, bulk density, stone volume and weathering
		Root penetration	Root explorable volume of horizon, Rooting depth of profile
Soil water tension	Soil-water adhesion	Soil water holding capacity	Soil water tension curve
	Lithology, irrigation	Salinity	Electrical conductivity, soluble salts
Soil water composition	Natural background, pollution	Soil water composition	Pollutant content and availability
	Anoxia	Oxygen availability	Air capacity

Table 4. Biochemical soil attributes.

Name	Code	Unit of measurement
Total organic carbon	Corg	g C kg^{-1} soil
Total extractable carbon	Cext	g C kg^{-1} soil
Humic and fulvic acid carbon	Cha + fa	g C kg^{-1} soil
Humification degree	DH	mg Cha + fa mg Cext^{-1} 100
Microbial biomass carbon	Cmic	mg C kg^{-1} soil
Basal respiration	Cbas	mg $\text{C–CO}_2\ \text{kg}^{-1}$ soil
Cumulative respiration, C–CO_2 total production at 28th day	Ccum	mg $\text{C–CO}_2\ \text{kg}^{-1}$ soil
Metabolic quotient	qCO_2	mg $\text{C–CO}_2\ \text{Cmic}^{-1}\ \text{h}^{-1}$
Mineralization quotient	qM	$(\text{Ccum Corg}^{-1}) \times 100$

Table 5. Classes of biological parameters. The lower the class the higher the soil microbiological stress.

Parameters	Classes				
	1	2	3	4	5
Organic matter (%)	< 1	1–1.5	1.5–2	2–3	> 3
Basal respiration (ppm)	< 5	5–10	10–15	15–20	> 20
Cumulative respiration (ppm)	< 100	100–250	250–400	400–600	> 600
Microbial biomass carbon (ppm)	< 100	100–200	200–300	300–400	> 400
Metabolic quotient	> 0.4	0.3–0.4	0.2–0.3	0.1–0.2	< 0.1
Mineralization quotient	< 1	1–2	2–3	3–4	> 4

Table 6. The LFA method (Tongway and Hindley, 2004) uses 13 soil surface field indicators, determined in query zones, and used to calculate three composite indices (Stability, SI; Nutrient Cycling, NC; Infiltration/Runoff, IR).

Indicator	Aim and unit of measure	N. of classes	SI	IR	NC
Rainsplash protection	Protection offered to soil by perennial vegetation, rocks, and woody material (as overall % cover)	5	X		
Perennial vegetation cover	Contribution of below-ground biomass of perennial vegetation to nutrient cycling and infiltration processes (estimated as % canopy cover of perennial plants)	4		X	X
Litter cover	Contribution of litter material (including ephemeral herbage such as living annual plants) to nutrient availability, as % litter cover plus thickness	10	X	X	X
Litter origin	Contribution of litter material (including ephemeral herbage such as living annual plants) to nutrient availability, with reference to its origin (transported or local)	2		X	X
Litter decomposition	Contribution of litter material (including ephemeral herbage such as living annual plants) to nutrient availability, with reference to its degree of incorporation to soil	4		X	X
Cryptogam cover	Contribution of algae, fungi, lichens, mosses and liverworts to soil surface stability and nutrient availability, as % cover of cryptogams visible on the soil surface	5	X		X
Crust brokenness	Contribution of soil crust to contain soil loss by erosion and to increase surface stability, assessed as crust condition, or brokenness	5	X		
Erosion type and severity	Evidence of recent/current erosion processes as indicator of local instability conditions, as type (5 classes) of process, and its severity (4 classes)	20	X		
Deposited materials	Presence of material transported from upslope as indicator of local instability conditions, as % cover plus thickness	4	X		
Surface roughness	Contribution of soil surface roughness to slow outflow rates and increase infiltration, as average relief (mm)	5		X	X
Surface resistance to disturbance	Contribution of soil surface resistance to mechanical disturbance to contain soil loss by erosion, as resistance of dry soil surface to penetration	5	X	X	
Soil slaking	Contribution of soil surface stability under rapid wetting to contain soil loss by erosion, as revealed by slaking test	5	X	X	
Texture	Role of soil surface texture with regard to surface permeability, as texture of the 0 to 5 cm topsoil manually estimated in the field	4		X	

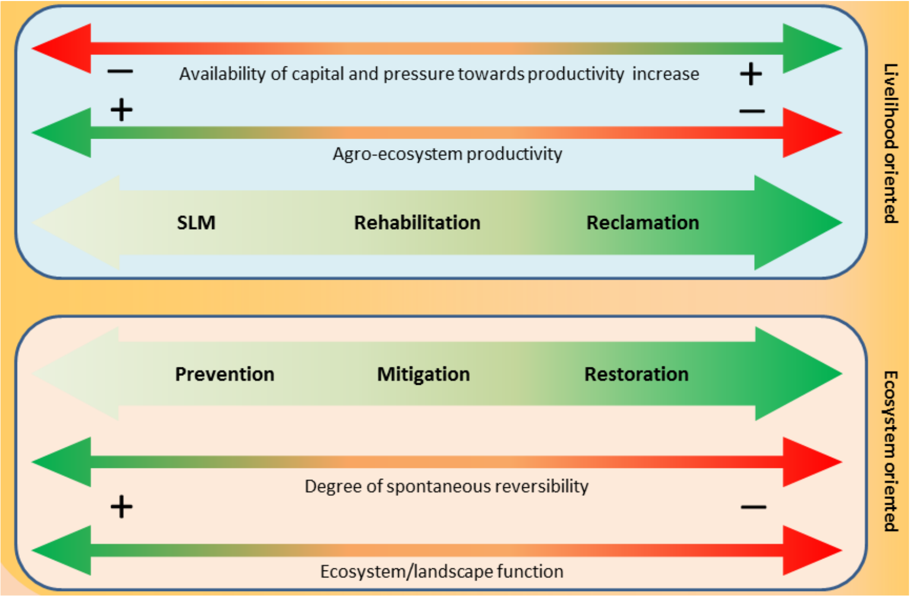

Figure 1. Soil restoration strategies, either livelihood or ecosystem oriented.

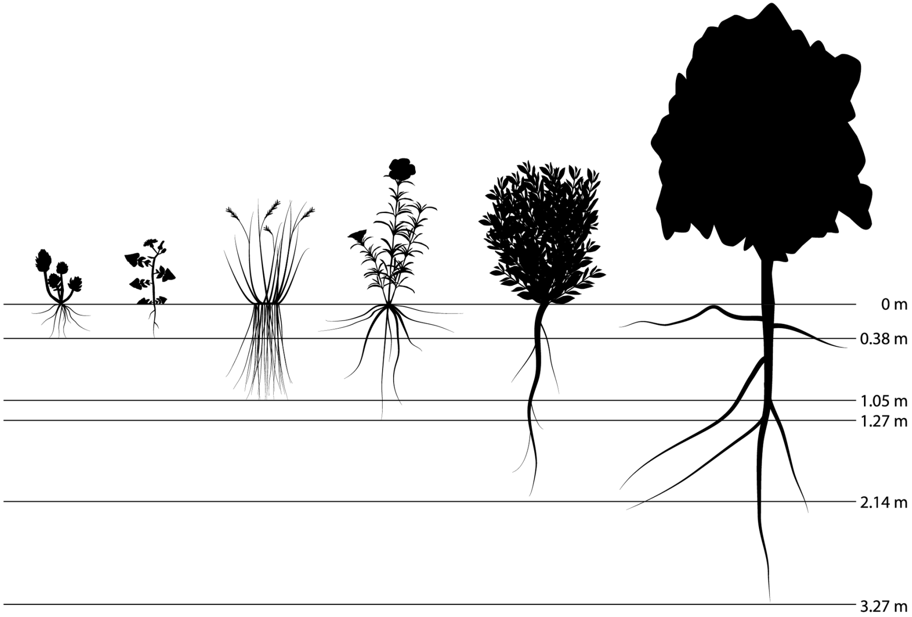

Figure 2. Rooting depths illustrated as schematic drawings of individual plants using approximate geometric mean values for six growth form categories (from left to right): succulents, annual herbs, perennial herbs, dwarf-shrubs, shrubs and trees. Root depths means were retrieved from Schenk and Jackson (2002).

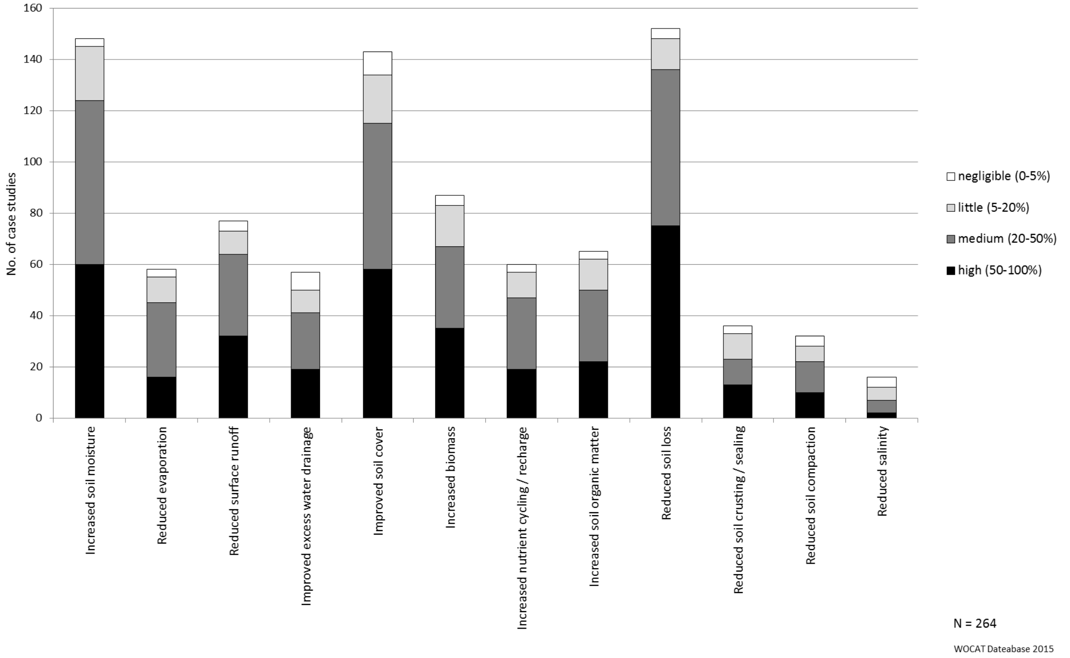

Figure 3. Soil-related ecological impacts of SLM practices in drylands (Source: WOCAT, 2015).

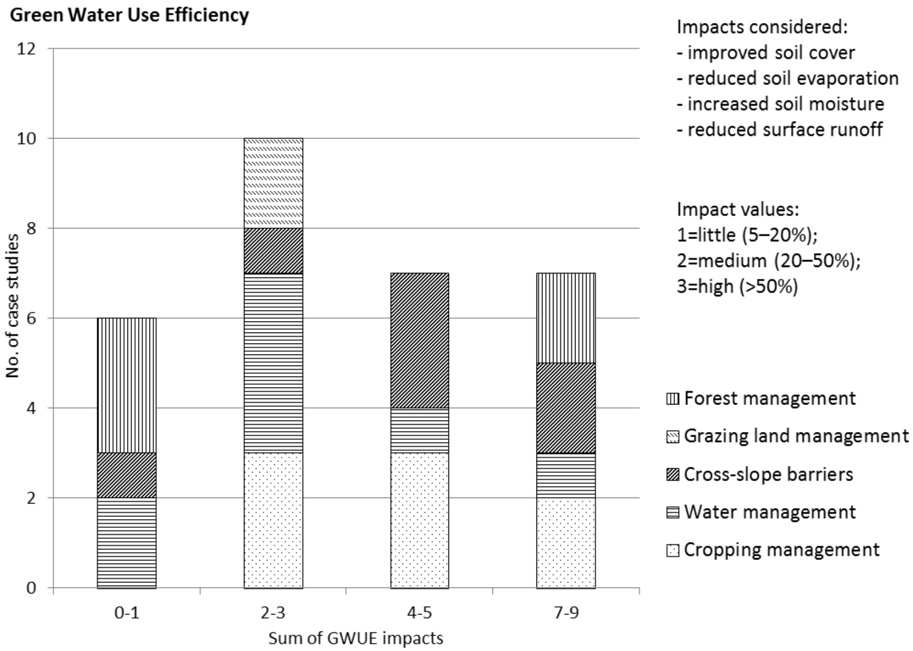

Figure 4. Aggregated impacts of SLM practices in regards to Green Water Use Efficiency (Source: Schwilch et al., 2014).

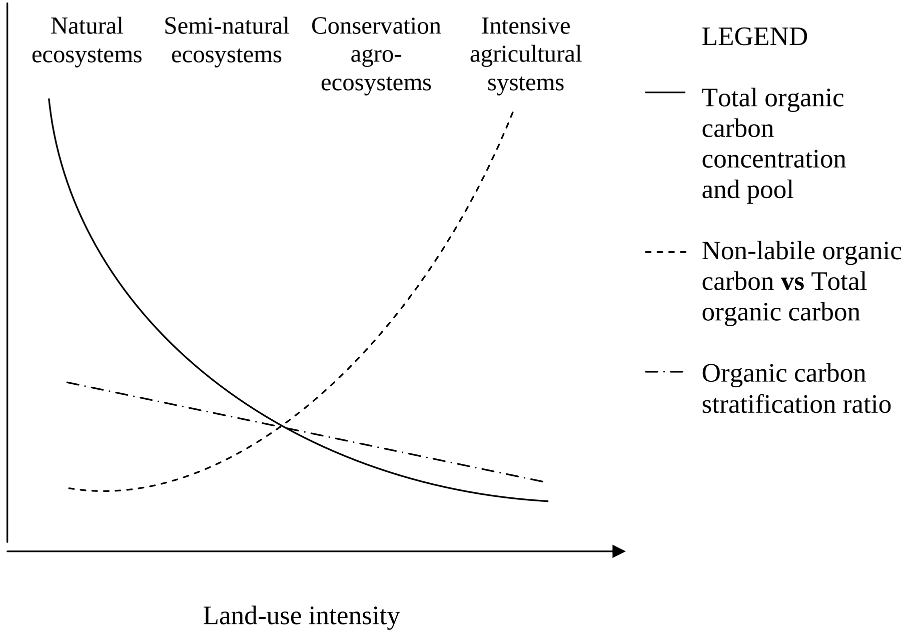

Figure 5. Land-use intensity effects on soil organic carbon dynamics.