BURLEIGH DODDS SERIES IN AGRICULTURAL SCIENCE

# Managing soil health for sustainable agriculture

## Volume 2: Monitoring and management

Edited by Dr Don Reicosky, Soil Scientist Emeritus
USDA-ARS and University of Minnesota, USA

E-CHAPTER FROM THIS BOOK

burleigh dodds
SCIENCE PUBLISHING

# Maintaining soil health in dryland areas

*Pandi Zdruli, Centre International de Hautes Etudes Agronomiques Méditerranéennes (CIHEAM), Italy; and Claudio Zucca, International Center for Agricultural Research in the Dry Areas (ICARDA), Morocco*



## 1 Introduction

How healthy are the dryland soils? The 'healthy' concept is unavoidably linked with the other term known as soil quality (Karlen et al., 1997) involving various characteristics that summarize the inherited value of the soil, which is a very dynamic and complex ecosystem regulated by the interaction of physical, chemical and biological processes acting simultaneously. Therefore, maintaining soil health in dryland soils requires in the first place a profound investigation of their inherited properties including their intrinsic limitations.

A decade ago the Agro Ecological Study (Fischer et al., 2006) estimated that 10.5 billion hectares of land, more than three-quarters of the global land surface, excluding Antarctica, suffer from severe to incipient soil constraints for low-input crop production. Overall, 13% of the global land surface is too cold, 12% is too steep meaning these areas are not suitable for crop production and about *27% is too dry* (Fig. 1). For the remaining 48% of the global land cover, about 65% is characterized by unfavourable soil conditions, with multiple constraints such as limited soil depth, high shrink/swell potential, high mechanical impedance, impeded drainage, low water-holding capacity, low fertility, poor soil texture and structure properties, stoniness, and specific soil chemical conditions such as natural salinity, sodicity, gypsum, and high aluminium content in the case of acid sulphate soils. Climate change scenarios increasingly indicate that drylands could experience significant

http://dx.doi.org/10.19103/AS.2017.0033.36


Chapter taken from: Reicosky, D. (ed.), *Managing soil health for sustainable agriculture Volume 2: Monitoring and management,* Burleigh Dodds Science Publishing, Cambridge, UK, 2018, (ISBN: 978 1 78676 192 7; www.bdspublishing.com)

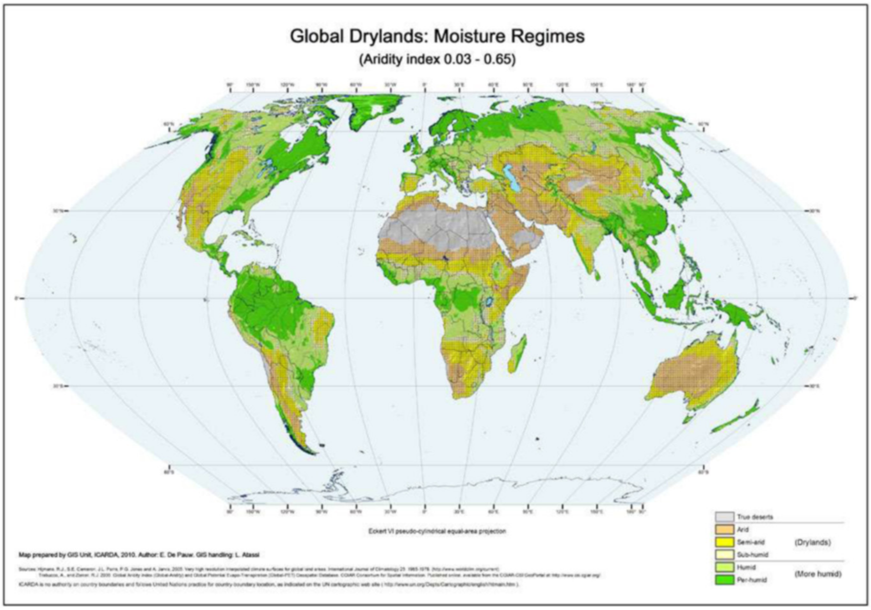


**Figure 1** Global distribution of drylands. Source: Published online, available from the CGIAR-CSI GeoPortal at: http://www.csi.cgiar.org/.NB: Note that the map uses the AI threshold index of 0.03.

changes in temperature and precipitation regimes (Rutherford, 2017), drought frequency would increase (IPCC, 2014), and dryland area could expand (Feng and Fu, 2013), hence the situation may further decline.

Many of the above-mentioned soil constraints are present in the drylands, where the lack of water makes the situation even harder. One of the most well-known criteria to define the drylands is the aridity index (AI) calculated on the ratio between mean annual precipitation and mean annual evapotranspiration in a given area. This way drylands are sub-divided into four categories: i) hyperarid representing the real deserts AI < 0.05, ii) arid 0.05 < AI < 0.20, iii) semi-arid 0.20 < AI < 0.50 and iv) dry sub-humid 0.50 < AI < 0.65 (Middleton and Thomas, 1992; Hulme, 1996; Safriel and Adeel, 2005; Mortimore et al., 2009). The climate of the area is arid (average annual rainfall of about 140 mm/yr), with precipitations concentrated during winter mostly in torrential form.

The main focus of the United Nations Convention to Combat Desertification (UNCCD.1) is on land degradation occurring in *arid, semi-arid* and *dry sub-humid areas*. Nevertheless, the UNCCD has been endorsed by almost all the countries no matter in which climatic domain they reside. Therefore, the focus of UNCCD has expanded to deal with land degradation, desertification and drought globally, although desertification mapping has proven to be cumbersome (Zdruli et al., 2017a) due to many interlinked facets. The link between deterioration of soil health and desertification expansion is one of the most visible consequences where land degradation and desertification occur.

Drylands are home to two billion people and 90% of them reside in the developing countries that cover 72% of the global dryland area (MEA, 2005). The economical value of drylands is enormous as they host 50% of the global livestock, and 30% of all presently grown crops originate from them (UNCCD.2). Moreover, crop cultivation in the drylands dates back millennia (Avner, 1998). However, despite the paramount importance of these soils, the economic cost of desertification and land degradation has been estimated at about US$41 billion (UNCCD.2). Degradation processes include soil erosion, nutrient and soil organic matter (SOM) depletion, water scarcity, increased salinity built up mostly due to poor quality irrigation water, and overall disruption of the soil's ecosystem services and functions that lead to crop failures and increased hardships for the already overall-poor dryland population.

Drylands are present in all continents. In North America they cover large parts of the US southwest in Nevada, Arizona, southern California, southern Utah and southwest New Mexico (Feng and Fu, 2013). By the end of this century, the arid regions are projected to expand to occupy most of New Mexico, western Texas and most of northern Mexico. The semiarid lands will also expand eastward by 2–3 degrees of longitude in the Great Plains of the USA (Feng and Fu, 2013). In Europe drylands mark 33.8% of the territory of the Mediterranean European Union member states, from a maximum of 69% in Spain, down to a 12% of France (Zdruli, 2014). Dryland areas in Western China cover about 40% of the country's total land area and are very vulnerable to drought and desertification. About 27% of the country is affected by severe land degradation, creating livelihood risks and vulnerability for several hundred million people (IFAD, 2016, based on data sources from https://www.thegef.org and Asian Development Bank, 2010).

In September 2015, the UN General Assembly approved 17 Sustainable Development Goals (SDGs). Among them, SDG 15 calls to 'Sustainably manage forests, combat desertification, halt and reverse land degradation, and halt biodiversity loss'. SDG 15.3 specifically tackles land and soil asking that 'By 2030, combat desertification, restore degraded land and soil, including land affected by desertification, drought and floods, and strive to achieve a land degradation-neutral world'. This was a historic shift from the previous Millennium Development Goals (MDGs) because from now on all countries have an equal share of responsibility for the well-being of the planet and to protect natural systems that are on the verge of collapse around the world. Drylands are the most fragile among them.

## 2 Formation and properties of dryland soil

Dryland soil pedogenesis is obviously conditioned by all five soil-forming factors (climate, parent material, relief, biota and time as described by Jenny (1941)), but the climate expressed by aridity and high temperature becomes dominant as the latter has slowed down and constrained the processes of soil formation, at least since the onset of the present-day aridity conditions going back thousands of years.

From the geo-morphological perspective, due to their worldwide distribution, dryland soils are present in a variety of settings spanning from fluvial and lacustrine landforms to sandy aeolian and loess deposits. Geo-morphological processes in the dry areas show some distinct characteristics such as the ephemeral nature of the streams and rivers that in many cases do not end up in the sea or oceans but instead in inland depressions that could latter develop into salt lakes. Aeolian sand encroachment is also typically affecting soil formation through the continuous movement of parent materials from one place to the other (Driessen and Dudal, 1991).

In the highlands, and on the upstream pediments and fluvial deposits of the dryland watersheds, soils are most typically shallow, eroded, weakly developed, and alternating with rock outcrops (Fig. 2). These soils are mostly sandy, are mixed with lower amounts of clay and silt, can have over 35% rock fragments or gravel, can be cemented on the surface and throughout the soil profile, and can have a high pH depending on the nature of the parent material. They are typically excessively or somewhat excessively drained and remain as barren land or are sometimes used for low-intensity grazing by camel, sheep or goat. Under arid to semi-arid conditions, such soils frequently have less than 5% vegetation cover by desert plants. They could be typically classified as Torriorthents or Torrifluvents (Fig. 2 and 3) according to the Soil Taxonomy (Soil Survey Staff, 2014) or as Leptosols, Regosols or Fluvisols according to the World Reference Base (WRB) system (International Union of Soil Sciences (IUSS) Working Group WRB, 2015). From the soil health perspective, soils like this are characterized by reduced microbial activity and low potential for biomass productivity.

On the intermediate to lowland areas, on gently sloping to flat morphologies, the deposits are less abundant in stones and pebbles, and soils tend to be moderately deeper. Sand- and gravel-dominated formations are frequent and mixed with sandy skeletal and silty/clayey formations that could reach considerable depth in the alluvial fans (Fig. 4). The latter are most typically classified as Fluvents or as Psamments if dominated by sandy layers, which in some cases can be ascribed to aeolian deposition. Psamments (Soil Survey Staff, 2014) or Arenosols (IUSS Working Group WRB, 2015) are widespread in the drylands (Fig. 5). They have very high permeability and low water-holding capacity because the sand in the soil is not graded and varying degrees of coarseness are constantly mixed throughout the soil. Because most sands are highly siliceous, Arenosols are also extremely low in all essential nutrients, hence their soil health is rather weak. Their water infiltration rate is very high, thus they are very

(a) (b)

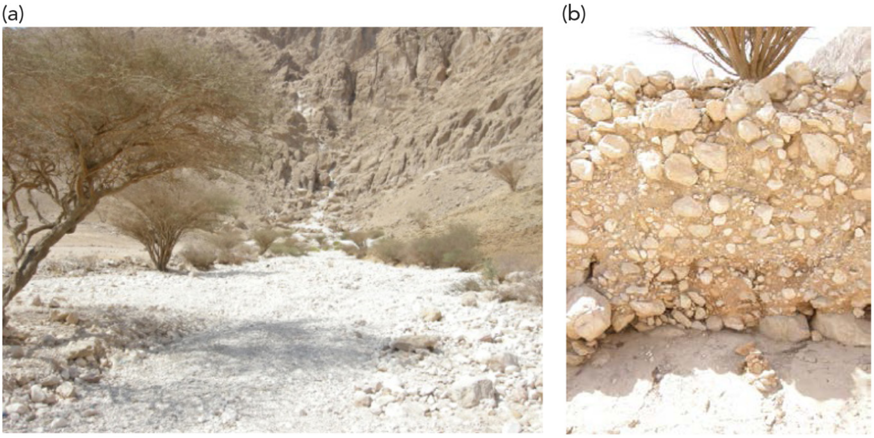

**Figure 2** Typical landforms and soils located in the upper parts of dryland watersheds. (a) Upper part of the White Wadi at the foot slopes of Jebel Hafeet mountain in the Mezyad desert of Al Ain, United Arab Emirates. Photo taken by P. Zdruli in 2016. (b) Soil profile from the same area. ST (Soil Survey Staff, 2014): Typic Torriorthents, sandy skeletal, mixed, hyperthermic. WRB (IUSS Working Group WRB, 2015): Calcaric, Skeletic Fluvisol (Yermic/Aridic, Arenic/Loamic/Siltic).

**Figure 3** Other examples of arid soils. Soil profile in the Mezyad desert, Al Ain, UAE. Photo taken by Zdruli. ST (Soil Survey Staff, 2014): Typic Torrifluvent, silty clay, mixed, hyperthermic. WRB (IUSS Working Group WRB, 2015): Calcaric Fluvisol (Yermic/Aridic, Clayic/Loamic/Siltic).

**Figure 4** Prof Zdruli showing a profile exposed in a cemented gravelly fluvial fan deeper than two metres in the Mezyad desert, Al Ain, UAE. ST (Soil Survey Staff, 2014): Typic Torrifluvent, skeletal, mixed, hyperthermic, WRB (IUSS Working Group WRB, 2015): Calcaric, Skeletic Fluvisol (Yermic/Aridic, Arenic/Clayic/Loamic/Siltic).

vulnerable mostly to wind erosion. They show weak pedogenic development and have a distinct structureless nature, and their chemical properties derive from the parent material. Their management must deal with low coherence, low nutrient storage capacity and high sensitivity to erosion, which are serious limitations of sandy soils in the drylands. Uncontrolled grazing without appropriate soil conservation measures can easily make them unstable and revert them to shifting sand dunes.

In the lowlands, sandy/clayey alluvial deposits are most frequent and soils are deeper. Local depressions are periodically flooded by either surface water or groundwater. Here the dry conditions can favour precipitation and accumulation of soluble salts after water evaporation. This may typically lead to the formation of saline soils (Solonchaks according to the WRB), and/or soils whose exchange complex and soil solution are enriched in sodium (Solonetz according to the WRB). Other typical dryland soils characterized by redistribution and accumulation of solutes are the Calcisols, characterized by calcic or petrocalcic horizons strongly enriched in calcium carbonate; the Gypsisols, having gypsic or petrogypsic horizon within 125 cm from the surface; and the Durisols that show accumulation and cementation by secondary silica.

Salinity in soils is both a natural process as well as a human-induced one. Salinity built up due to irrigation is called secondary salinization. When soils turn saline they contain soluble salts in excessive concentrations that consequently impair crop growth. Strong salinity is most typically present in the drylands, and saline soils are characterized by low organic matter content, very weak structure development, high clay content and limited soil horizon differentiation. Saline surface area altogether may have reached a 1 billion ha spread in more than 100 countries and most of them are in the dryland areas (Food and Agriculture Organization – Intergovernmental Technical Panel on Soils (FAO ITPS), 2015). Salt-affected soils (or Solonchaks) are extensive in the arid and semi-arid regions of North Africa, the Near East, former Soviet Union and Central Asia, India, Pakistan, Iran, Iraq and Australia (IUSS Working Group, 2014). Sodic soils (or Solonetz) typically occur in steppe climate regimes with a total annual precipitation of 400–500 mm or less, mostly in poorly drained flatlands. Their major distribution occurs in Ukraine, the Russian Federation, Eastern Europe, China, India, the USA, Canada, Southern and Eastern Africa, and Australia.

**Figure 5** Example of Arenosol on alluvial plain encroached by Aeolian sand. Photo taken by C. Zucca. Feriana (Tunisia), 2006 (Previtali et al., 2014). WRB (IUSS Working Group WRB, 2015): Haplic Arenosol (Aeolic/Protocalcic/Thapto Luvisolic).

**Figure 6** Another type of arid soil. ST (Soil Survey Staff, 2014): Lithic Haplocalcids, sandy skeletal, mixed, hyperthermic. WRB (IUSS Working Group WRB, 2015): Hyperskeletic/Skeletic, Leptic Calcisol (Yermic/Aridic, Arenic/Siltic).

In addition to the above-mentioned soils, dryland areas also have to a limited extent a variety of other soils that include those typical for the humid regions, such as Vertisols, Luvisols and Kastanozems (IUSS Working Group, 2014) (Fig. 6).

# 3 Soil health in the drylands

The term soil health is rather recent in soil literature but has gained strength especially in the wake of population growth, food security (Brevik, 2009; Amundson, 2015) and environmental concerns about soil's contamination. It is also for these reasons that watchwords such as 'healthy soils produce healthy food and sustain healthy people' are becoming ever more common and frequent. Soil is a living biological system and as such is very vulnerable to soil degradation especially to soil erosion and loss of carbon (Kibblewhite et al., 2008; Lehman et al., 2015). Furthermore, environmental sustainability, human health and the overall well-being of entire societies depend on soil health as history has shown (Diamond, 2005). Finally, soil health is defined as the continued capacity of the soil to maintain functions and provide habitat and energy for microbes and animals, and sustain plants, animals and humans (Laishram, 2012).

Peer-reviewed scientific research (Acton and Gregorich, 1995; Sherwood and Uphoff, 2000; Doran et al., 2002; Doran, 2002; Karlen et al., 2017) has shown that many of the same farming and grazing practices to improve soil health can also reduce nutrient losses to groundwater and surface water, reduce greenhouse gas emissions, reduce erosion, increase yields, suppress plant diseases, and provide pollinator and other wildlife habitat. Nevertheless, it is widely accepted that soil health is most directly related to the SOM content, which is considered as the 'elixir of life' for the well-being of the soil itself and the ecosystem functions and services it provides (Weil and Magdoff, 2004; Lal, 2016).

Most importantly the increase in soil organic carbon (SOC) leads to enhanced nutrient availability, reduced erodibility, greater water-holding capacity, increased rate of water infiltration (therefore reduced run-off), and other benefits. Finally increased carbon sequestration in the soil is one of the most efficient mitigation remedies to control climate change and maintain yields (Paustian et al., 2016).

Soil health issues in the dryland areas are somehow different from those in more humid ones. First, this depends on the land use/land cover pattern with the grazing lands occupying the largest areas while agriculture land is less available largely under rainfed conditions. Therefore, the amount of SOC they hold is much less than the humid soils (Lal, 2004). Consequently, grazing and farming management practices require special attention and need to be tailored based on local bio-physical and socio-economic conditions (Yirdaw et al., 2017).

We describe below the most important critical issues that need further attention and research efforts to maintain soil health in the drylands and more in particular towards their sustainable use and management.

# 4 Dryland soil research priorities

## 4.1 Nutrient cycling

Nutrient cycling and the release of nutrients is one of the primary outcomes of the soil's supporting services. It is widely recognized that such a process is the largest contributor of goods and services providing annually about 51% of the total value (US$33 trillion) of all ecosystem services combined (FAO, 2011) despite the criticism that not all ecosystem services have a price tag. Nutrient cycling in arid drylands in particular takes a more complicated path as such soils are either covered by mineral crusts that can reduce infiltration and generate flashfloods or by a biological crust made of cyanobacteria (Rutherford et al., 2017) mixed with mosses and lichens (Budel, 2001) that provides few organic sources for the release of nutrients, other than mineral or dust depositions. Since dry soils have a much limited number of microorganisms compared with wetter soils, the invertebrate macro-decomposers such as termites and darkling beetles and other soil dwellers play a major role in the nutrient cycling process (MEA, 2005).

Drylands could be particularly vulnerable to climate change (Rutherford et al., 2017) as the predicted increase in aridity could disrupt the nutrient cycles of C, N and P as shown by Delgado-Baquerizo et al. (2013), who analysed 224 soil samples from drylands spanning in all continents, except Antarctica. They found a negative effect of aridity on the concentration of soil organic C and total N, but a positive effect on the concentration of inorganic P, suggesting that any predicted increase in aridity with climate change will probably reduce the concentrations of N and C in global drylands, but increase that of P. There are still many unknown aspects in nutrient cycling of drylands where research is needed.

## 4.2 Soil biota

Only about 1% of the soil microorganisms (bacteria and fungi) have been identified (Wall et al., 2001, 2012), and as many as 99.5% of all soil organisms have not been cultured (Alain and Querellou, 2009). The biological properties of soils can reveal an important component of soil health in drylands. According to Dickinson et al., (2005), soil biodiversity is a major factor for maintaining ecosystem functions and soil health in disturbed environments. Several biological indicators have been proposed to assess soil improvement from restoration of the degraded lands, including soil microbial biomass and number, soil microbial activity, soil microbial diversity and community structure, and soil mesofauna composition (Bloem et al., 2005; Costantini et al., 2016). The scientific knowledge dealing with soil biota in the drylands is yet limited. The future challenges in this research field will be directed towards standardizing methodologies, in order to provide quick, reliable and inexpensive information (Costantini et al., 2016).

## 4.3 Organic matter content and carbon sequestration

Drylands store much less SOC per hectare than humid regions, but the vast surface area they cover globally make them a highly significant global C sink (Lal, 2009; Scharlemann, 2014; Zdruli et al., 2017b). Estimates show that drylands could store 27% of the global SOC stocks and up to 97% of the total soil inorganic reserves (Yirdaw, 2017). In fact the potential for storing SOC in dryland soils may be comparable on a per-hectare basis to that of the humid areas because, as opposed to soils in humid regions, dryland soils have suffered previous higher losses of OC from degradation (Farage et al., 2007) so there is 'sink capacity' that could be filled up through sustainable soil management practices.

The '4‰- Soils for Food Security and Climate Initiative' launched in 2015 as part of the Paris Climate Agreement at COP 21 aims to increase the SOM content and promote carbon sequestration in the world's soils. This could be achieved through the application of agricultural practices adapted to local situations economically, environmentally and socially, applying the principles of agro-ecology, agroforestry, conservation agriculture and landscape management. Despite scepticism (Stabinsky, 2015; van Groenigen et al., 2017) there is no doubt that increasing SOM has enormous benefits for both soil qualities and climate change mitigation (Smith et al., 2014; Lal, 2015). What the real contribution of the drylands could be in global carbon sequestration stocks is however yet to be quantified.

## 4.4 Erosion control and soil conservation

Both wind and water erosion have impacted drylands for millennia but wind erosion is more typical for these regions. On the positive side, wind erosion from drylands has often 'fertilized' the soils of the nearby regions mostly with P and K. There is evidence that Sahara dust (Fig. 7) has not only reached the countries of the Northern Mediterranean and the Middle East but as far as the Amazon basin (UNEP, WMO, UNCCD, 2016). Clearly, this does not in any way compensate the huge on-site costs of soil loss. Research on erosion is rich for the drylands and a wide range of soil conservation technologies and approaches such as terracing, water harvesting and controlled grazing are available worldwide (Liniger et al., 2011; Marques et al., 2016). However, the international community is increasingly aware that sustainable land management (SLM) options should be fitted to the social, economic and ecological contexts. The high contextual diversity of drylands prevents the design and application of uniform 'blanket' policies. In-depth research must identify suitable soil conservation measures to generate the highest soil health benefits.

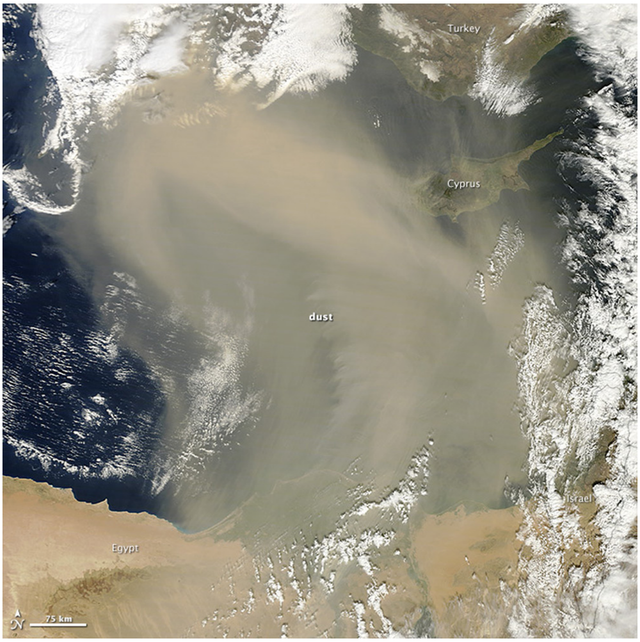


**Figure 7** Sahara dust storms affecting Southern Europe and Turkey. Dust storm event of 15 January 2014 over Cyprus and Turkey. (http://earthobservatory.nasa.gov/NaturalHazards/view.php?id=83268) (We acknowledge the use of data products or imagery from the Land, Atmosphere Near real-time Capability for EOS (LANCE) system operated by the NASA/GSFC/Earth Science Data and Information System (ESDIS) with funding provided by NASA/HQ).

## 4.5 Rainwater harvesting

The main natural constraining factor of drylands is the lack of water. This is influenced by the limited amount of rainfall, its unequal annual distribution and its torrential nature. When it rains in the drylands, every drop counts and should be collected (Oweis and Hachum, 2006). A good example (Abdalla, 2016) of this is given in the section 'Case Study' for the reclamation of the Wadi Kharrouba in Egypt. There are a few traditional rainwater harvesting techniques that include oasis water collection and galleries for water catchment defined as qanat, falaj, foggara and kareez (Laureano, 2001). More modern rainwater harvesting techniques include micro and macro catchment water harvesting, and rooftop or courtyard rainwater harvesting (Marques et al., 2016). Similar to dryland soil conservation options, strategic research on water harvesting should target landscape and watershed planning to maximize water harvesting efficiency.

## 4.6 Irrigation efficiency and salinity/sodicity control

The expansion of large-scale and more efficient irrigation systems had contributed to increased production and improved economic welfare of rural dryland populations, but unavoidably this was associated with salinity build-up. As an example 1 M ha of agricultural land was turned saline in Egypt due to poor-quality irrigation water and irrigation mismanagement (Goma, 2005). Irrigation in many cases has been unsustainable without extensive public capital investment and it was associated with many environmental issues other than salinization. The issues include waterlogging, water pollution, seawater intrusion into the fresh aquifers (Amores et al., 2013), eutrophication, and unsustainable exploitation of groundwater aquifers with severe consequences on the drylands' provisioning services.

In Iraq, due to lack of investments to improve irrigation and drainage systems since the early 1980s, a situation exacerbated by recent wars and conflicts, soil salinity has spread across much of the irrigated areas in central and southern parts of the country. At present, about 70% of the country's irrigated area suffers from varying levels of salinity and an estimated 25 000 hectares of farmland are abandoned each year because of elevated salt levels (ICARDA Iraq Salinity Project, 2012).

Research should focus on water use efficiency, implementation of modern irrigation systems and on the nexus of soil-water-crop-energy to support crop yields, soil quality and soil health. In addition, salinity management requires avoiding salinity build-up and then leaching of soluble salts with freshwater especially during the rainy season. Deep ploughing, subsoiling in compacted soils with laminated or platy structure, application of organic farmyard manure and gypsum, and green manuring or inoculation of beneficial soil microbes are some of the areas for further research. Moreover, research must focus also on salt-tolerant crops (Glenn et al., 1999) known as *halophytes* that are extremely beneficial and much cheaper for the management of saline soils. The most important are quinoa (*Chenopodium quinoa* Willd), barley (*Hordeum vulgare* L.), rye (*Secale cereale* L.), salt-tolerant varieties of alfaalfa, trees (*Eucalyptus camaldulensis* Dehnh.) and saltbushes (*Atriplex* spp.) Another promising halophyte is the sea buckthorn (*Hippophae* L.), a deciduous shrub that grows natively across northern Eurasia and could be suitable for the dry sub-humid drylands.

Vertical mulching with thick inert soil layers (Mostafa, 2014) also proved to be effective in increasing water-holding capacity and strongly decreasing soil salinity under arid conditions thanks to improved soil moisture regime and reduced evaporation (Tejdor et al., 2007).

### 4.7 Biochar and biopolymers

Biochar is another option to improve soil fertility provided there is availability of organic materials – a vast body of research is already available on this subject (Laghari et al., 2016). Finally, the use of synthetic polymers and biopolymers to improve soil physical properties by enhancing the soil structural stability and consequently reducing soil erosion and run-off is a new frontier of research (Maghchiche et al., 2010).

## 5 Options and solutions for dryland soil health improvement

The impacts of climate change on drylands are more evident than on other areas (Feng and Fu, 2013) and the unavoidable answer would be adaptation. The International Center for Agricultural Research in the Dry Areas (ICARDA, 2015) is in the front line of developing climate-smart technologies to improve food security and livelihoods in drylands. These technologies include the development of improved varieties of crops and forages with enhanced heat and drought tolerance, soil conservation and water harvesting packages, water-efficient irrigation systems, land rehabilitation technologies for degraded rangelands, improved livestock breeds and breeding systems, and innovation packages to enable small farmers to practice conservation agriculture based on small implements (e.g. raised-bed seeders) locally engineered and produced. *No-till seeding* and *raised-bed technologies* are efficient methods to implement for reduced soil disturbance and increase water use efficiency.

Technologies that enhance soil health include crop-fallow rotation systems fostering the soil food chain, sustaining natural pest control, and lessening the adverse agronomic and ecological impacts of monoculture (Peairs et al., 2005; Ando et al., 2014). Other benefits of such cropping systems are the increased capacity of the soil to sequester carbon and improve the overall soil quality and ecosystem functioning (Tondoh et al., 2013). Mulching and composting by using all possible forms of organic residues also need to be promoted as an important component of soil health-oriented farming systems. In a more comprehensive concept the adoption of the principles of sustainable agronomic practices such as *conservation agriculture* could be an optimal solution also for the drylands (Serraj and Sidique, 2012; Bayala et al., 2012; Kassam et al., 2012).

No one should minimize the role of agricultural research in sustainable land and water management, supported by bioengineering and advanced technologies. However, research results need to be upscaled from the experimental sites into the farms of hundreds of thousands of small farmers spread throughout the drylands. Hence, the science-policy gap needs to be filled and only when local communities will benefit from these new technologies will they endorse them at a larger scale (Akhtar-Schuster et al., 2011). In this regard, a system research team at ICARDA has developed a geospatial 'option by context' tool to understand the role of socio-ecological contexts in SLM, and to plan the effective out-scaling of the SLM options by taking the contextual diversity/similarity into account (Le et al., 2016).

# 6 Case study

*A success story from the drylands of Egypt:* MARSADEV project aiming community management of natural resources to ensure food security in arid areas.

The MARSADEV project was operational for the period February 2014 to March 2017. Funding was provided by the Italian Ministry of Foreign Affairs – General Directorate for Cooperation and Development (IMFA-GDCD) through the Italian Food Aid Fund. Implementing agencies were the Ministry of Agriculture of Egypt and the Desert Research Center (DRC) of Marsa Matrouh – Egypt, while the Centre International de Hautes Etudes Agronomiques Méditerranéennes (CIHEAM) – Mediterranean Agronomic Institute of Bari (CIHEAM-IAMB) was the executing agency (Fig. 8).

The project implemented a number of natural resource base interventions to prevent environmental degradation of limited soil and water resources, combating land degradation and flooding through concrete actions on-the-ground. Traditional solutions based on local knowledge were integrated with state-of-the-art technologies to *recover degraded lands, prevent erosion, enhance water saving and harvesting, enrich soil fertility, improve crop yields, provide appropriate conditions for livestock management, and finally help to alleviate poverty and boost socio-economic conditions of the local Bedouin communities.*


**Figure 8** Location of the project area in the region of Matrouh, Western Coastal Egypt

A significant achievement of the project was the reclamation of Wadi Kharrouba, a barren abandoned watershed (13 ha), marked by intense gully erosion. The climate of the area is arid (average annual rainfall of about 140 mm/yr), with precipitations concentrated during winter in torrential form. Interestingly the area has been settled since the Roman times as demonstrated by ancient cisterns – some of them still functioning – and endless pottery scattered throughout. Other studies (Vetter et al., 2014) report similar findings and relate them with ancient watershed management methods. The main crops include olives, figs, rainfed barley and a few vegetable crops.

Wadi Kharrouba is a site for research and dissemination. A meteorological station, soil moisture control equipment and specially designed hydraulic sensors were implemented to measure surface water flows. Only this way the exact water balance inside the wadi could be established and the water washed away could be measured.

Land reclamation interventions included land levelling, dam construction, and establishment of semicircular terraces on the wadi's surrounding slopes to control erosion and provide additional income for the Bedouin farmers. Local drought-resistant plants such as *Opuntia ficus-indica*, *Atriplex littoralis* spp., *Moringa oleifera* and *Medicago arborea* were planted in semicircles. Soil health at levelled terraces was improved by the cultivation of *Vicia faba*, which, at the height of growing season, was ploughed and mixed with the soil to increase SOM and N contents in the soil.

In addition supplementary irrigation was provided in some parts of the wadi through the harvested water in an upland cistern. Measured data for the rainy season 2015–2016 (a particularly wet winter with a total rainfall of 230 mm) showed a total of more than 50 000 m³ of rainwater was stored in the terraced soil and 18 000 m³ of that water was still available in the soil (Abdalla, 2016) until late July 2016 (Fig. 9). If not for the land reclamation, this 50 000 m³ of water would

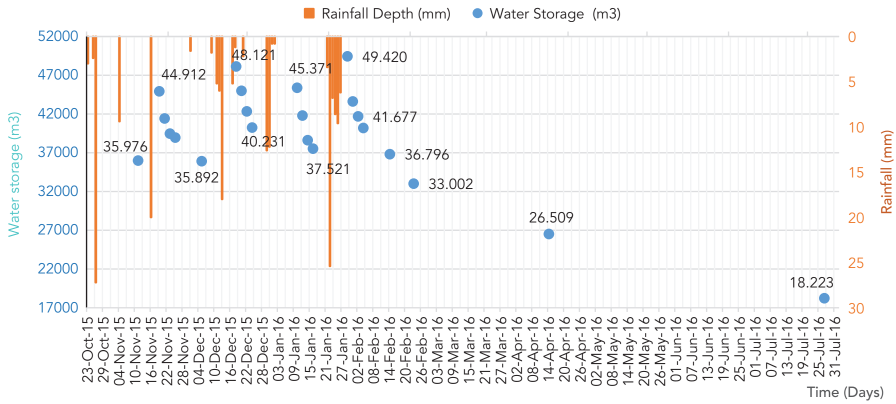


**Figure 9** Rainfall water and water storage in soils measured in 20 reclaimed terraces of Wadi Kharrouba during the monitoring campaign October 2015 to July 2016 (Abdalla, 2016).

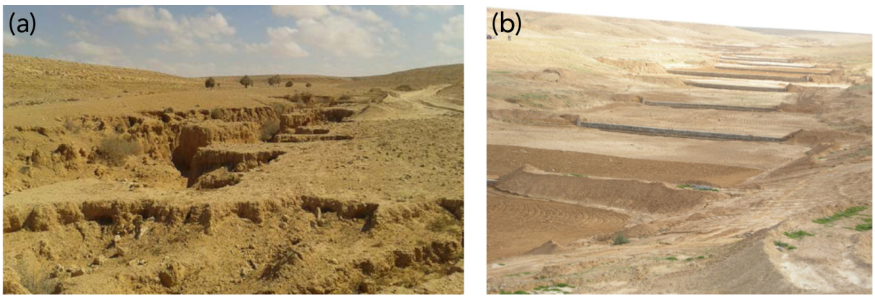


**Figure 10** Wadi Kharrouba before (a: 2014) and after (b: 2016) reclamation. Source: MARSADEV project (https://www.facebook.com/search/top/?q=marsadev%20project%20egypt).

have been lost. Instead, data for 2016–2017 showed the rainfall had been extremely low (less than 50 mm), which confirms the benefits of water harvesting inside the wadi.

The example of Wadi Kharrouba shows that 'greening the desert' is possible when innovation and tradition are complementary and local communities are both actors and players of the whole rural development process (Fig. 10).

# 7 Future trends

The Conference of Parties (COP 22) of the United Nations Framework Convention on Climate Change (UNFCCC) held in Marrakech, Morocco in November 2016 addressed a number of issues related to the future of drylands as summarized by the Consultative Group on International Agricultural Research (CGIAR) (2016): 'drylands' will expand by 11 percent by 2100 due to climate change. Fifteen out of 24 ecosystem services are already in decline, making drylands increasingly unproductive. About 10 percent of drylands are already degraded, and more land will continue to degrade in the upcoming years. Yet, drylands and agricultural research in drylands do not receive much attention or investment from the wider community of scientific research, development agencies, policy makers or the private sector. This is in part due to huge misconceptions or oversimplifications that ignore the complexity of dryland agricultural systems, in terms of both biophysical and socio-economic factors, and the valuable things we can learn about climate change mitigation and adaptation from examining the complex interactions of these factors in drylands'.

Researchers working on a European trans-national cooperation project (COST Action, 2016) conducted a survey to investigate the extent to which the research results are being applied to the Mediterranean Basin by analysing 36 restoration projects, mostly from the drylands (Nunes et al., 2016). They found poor monitoring of the projects' progress as one of the main shortcomings. In 22% of the projects surveyed, ecological restoration success was never evaluated, while long-term (at least 6 years) evaluation was performed in a mere 31% of the cases, using primarily plant diversity cover as indicators. Undesired restoration results (e.g. inadequate biodiversity) were reported for 50% of the projects. The experience described in the Case Study of Wadi Kharrouba in Egypt reaffirms that interacting with the local communities is vital for the success of dryland management and rehabilitation.

Given the particular nature of land use in drylands, which are dominated by rangelands or barren areas with less space for agricultural crops, focus should be placed on integrated approaches that preserve soil quality through sustainable grazing, for example, by avoiding overgrazing and encouraging rotational and controlled grazing. Developing drought- and salinity-resistant varieties for the most strategic dryland crops will reduce the negative effects of climate change as more SOC is deposited in the soil while the soil itself becomes healthier. Among these crops, wheat, maize, barley and sorghum, providing staple food for the people living in the semi-arid regions of Africa, Asia and Latin America, are paramount. Other basic crops include millet, lentil, fava beans, chickpea, figs, apricot and pistachios. Finally, much attention should be focused on sustainable management as dryland soils are fragile and vulnerable to adverse agronomic and grazing practices (Montanarella, 2015). To this end, further research is needed to respond to the key points raised by this chapter.

# 8 Conclusion

This article reviews the concepts and research issues related to soil health in drylands starting from the identification of the main properties, and the constraints of the dryland soils. The introductory section outlines the intrinsic limitations and the main degradation processes affecting the dryland soils, as recognized by international organizations and conventions such as the FAO (Agro-Ecological Zones) and the UNCCD. It points out, however, that due to their geographical extent drylands constitute an immense resource whose rehabilitation/restoration is high in the international agenda (e.g. as part of the SDGs). The second section summarizes some of the soil formation processes that are typical of the arid and semi-arid climates, by following a geomorphological approach. The main soil types developing in different landscape positions are briefly described, along with their vulnerability and health issues. The latter are briefly discussed in the next section with the aim of underlining the difference between soil health issues in dry versus humid regions. The fourth section reviews some key issues connected to the conservation and the enhancement of soil health in drylands, for which further in-depth research is likely to be needed in future. These include: nutrient cycling processes; the relationships between soil biodiversity and soil health in dry environments; the soil carbon storage potential of the dryland soils; the knowledge gaps about the effectiveness of soil conservation and rain water harvesting techniques; the efficiency of irrigation systems and management of secondary salinity; and a range of alternative approaches to enhance soil health including the use of biochar and biopolymers. In the final section, the possible options for sustainable intensification in drylands are taken into consideration, such as conservation agriculture (CA). Developing CA solutions and quantifying their sustained and multiple benefits requires long-term studies and monitoring. During the last three decades, important investments were made globally to establish long-term (decadal) research sites to quantify the impacts of CA on the soil. With few exceptions, these studies were conducted in developed countries and in temperate climate conditions, widening the technology gap between humid-rich and dry-poor regions. An interdisciplinary integrated approach will be necessary to quantify the impacts of these technologies in drylands: today soil is no longer viewed as a fundamental resource required to produce food – there is the realization that soil has an ecological function through the provision of ecosystem goods and services, including carbon sequestration.

# 9 Where to look for further information

Dryland literature is quickly expanding. The main source comes from UNCCD http://www2.unccd.int/ that offers a large variety of information sources both in terms of assessments and solutions to deal with drylands, land degradation, desertification and drought.

Global drylands: A UN system-wide response. prepared by the Environment Management Group (EMG) of the United Nations. The report responds to calls by governments for a UN system-wide response to land challenges. It sets out a common vision and agenda for UN-wide action on dryland management and its role in addressing climate change and food security through a positive development and investment approach, p. 132.

http://www.unccd.int/Lists/SiteDocumentLibrary/Publications/Global_Drylands_Full_Report.pdf

Other important sources include CGIAR's ICARDA research programme (http://www.icarda.org/) and the *International Crops Research Institute for the Semi-Arid Tropics* (*ICRISAT*) (www.icrisat.org/). The *International Fund for Agricultural Development* (*IFAD*) (https://www.ifad.org/) in 2016 published a very interesting report with a number of success story case studies included in the report *The Drylands Advantage: Protecting the environment, empowering people*.

In the scientific journals mention is made to *Land Degradation & Development* (Wiley); *Journal of Arid Environments*, *Arid Land Research and Management*, and *Science of the Total Environment journal* (Elsevier); *Natural Hazards Journal* (Springer); *Pedosphere* (China); *Soil Use and Management* (Wiley-Blackwell, British Soil Science Society); *Sustainability* (Multidisciplinary Digital Publishing Institute (MDPI), Basel, Switzerland); and *Encyclopaedia of Soil Science*, Third Edition (Lal, eds) published by CRC Press Taylor & Francis.

DesertNet International (DNI) is a scientific network for international research on desertification (http://www.desertnet-international.org/index.php) that brings together 334 experts in dryland research from 52 countries. DNI is composed of several working groups dealing with science-policy interface, dryland restoration, observation systems, economic drivers, and training and capacity building. The network publishes regularly three annual newsletters in English and is a good source of information for dryland research and management, including soil issues.

# 10 References

Abdalla, M. A. I. 2016. A rainfall-runoff model for water management in wadi systems based on hydropedological studies. Master thesis. CIHEAM Mediterranean Agronomic Institute of Bari, Italy.

Acton, D. F. and Gregorich, L. J. 1995. *The Health of our Soils: Toward Sustainable Agriculture in Canada*. Agriculture and Agri-food Canada, CDR Unit, 960 Carling Ave., Ottawa, ONK1A 0C6.

Akhtar-Schuster, M., Thomas, R., Stringer, L. C., Chasek, P. and Seely, M. 2011. Improving the enabling environment to combat land degradation: Institutional, financial, legal and science-policy challenges and solutions. *Land Degradation and Development* 22: 299–312.

Alain, K. and Querellou, J. 2009. Cultivating the uncultured: limits, advances and future challenges. *Extremophiles* 13, 583–94.

Amores, M. J., Verones, F., Raptis, C. and et al. 2013. Biodiversity impacts from salinity increase in a coastal wetland. *Environmental Science & Technology* 47(14): 6384–92. DOI:10.1021/es3045423.

Amundson, R., Asmeret Asefaw Berhe, A., Hopmans, J. W., Olson, C., Ester Sztein, A. and Sparks, D. L. 2015. Soil and human security in the 21st century. *Science* 348(6235). DOI: 0.1126/science.1261071.

Ando, K., Shinjo, H., Kuramitsu, H., Miura, R., Sokotela, S. and Funakawa, S. 2014. Effect of cropping and short-natural fallow rotation on soil organic carbon in the Eastern Province of Zambia. *Agriculture Ecosystems & Environment* 196: 34–41. DOI:10.1016/j.agee.2014.06.012.

Avner, U. 1998. Settlement, agriculture and paleoclimate in Uvda Valley, southern Negev desert, 6th–3rd Millennia BC. In *Water, Environment and Society in Times of Climatic Change* (A. S. Issar and N. Brown (Eds)). Kluwer Academic Publishers, Dordrecht, pp. 147–202.

Bayala, J., Sileshi, G. W., Coe, R., Kalinganire, A., Tchoundjeu, Z., Sinclair, F. and Garrity, D. 2012. Cereal yield response to conservation agriculture practices in drylands of West Africa: A quantitative synthesis. *Journal of Arid Environments* 78: 13–25.

Bloem, J., Schouten, A., Sørensen, S. J., Rutgers, M., Werf, A., Breure, A., Hopkins, D. and Benedetti, A. 2005. Monitoring and evaluating soil quality. In *Microbiological Methods for Assessing Soil Quality*. CABI Publishing, Wallingford, pp. 23–49.

Brevik, E. C. 2009. Soil health and productivity. In *Soils, Plant Growth and Crop Production*. Chapter 1 (W. Verheye (Ed.)). Encyclopedia of Life Support Systems (EOLSS), Developed under the Auspices of the UNESCO, EOLSS Publishers, Oxford, UK, pp. 1–26. http://www.eolss.net. Last accessed 10 March 2017.

Budel, B. 2001. Synopsis: Comparative biogeography and ecology of soil-crust biota. In *Biological Soil Crusts: Structure, Function and Management* (J. Belnap and O. L. Lange (Eds)). Springer-Verlag, Berlin, pp. 141–54.

Consortium of International Agricultural Research Centers (CGIAR). 2016. Now is the time to invest in drylands. http://drylandsystems.cgiar.org/content/now-time-invest-drylands [last accessed 20 March 2017].

Cost Action (2016). Cost Action ES1104 – draft white paper on the restoration of drylands. 8p. https://desertrestorationhub.com/about/ [last accessed 22 March 2017].

Costantini, E. A. C., Branquinho, C., Nunes, A., Schwilch, G., Stavi, I., Valdecantos, A. and Zucca, C. 2016. Soil indicators to assess the effectiveness of restoration strategies in dryland ecosystems. *Solid Earth* 7: 397–414. Doi: 10.5194/se-7-397-2016.

Delgado-Baquerizo, M., Maestre, F. T., Gallardo, A. and et al. 2013. Decoupling of soil nutrient cycles as a function of aridity in global drylands. *Nature* 502: 672–6. DOI:10.1038/nature12670.

Diamond, J. 2005. *Collapse: How Societies Chose to Fail or Succeed*. Viking Press, USA.

Dickinson, N. M., Hartley, W., Uffindell, L. A., Plumb, A. N., Rawlinson, H. and Putwain, P. 2005. Robust biological descriptors of soil health for use in reclamation of brownfield land. *Land Contamination & Reclamation* 13: 317–26 https://doi.org/10.2462/09670513.692.

Doran, J. W. February 2002. Soil health and global sustainability: translating science into practice. *Agriculture, Ecosystems & Environment* 88(2): 119–27.

Doran, J. W., Stamatiadis, S. and Haberern, J. 2002. Soil health as an indicator of sustainable management. *Agriculture, Ecosystems and Environment* 88: 107–10.

Driessen, P. M. and Dudal, R. (Eds). 1991. *The Major Soils of the World: Lecture Notes on Their Geography, Formation, Properties and Use*. Koninklije Worhmann, B.V., Zutphen, The Netherlands.

FAO. 2011. The state of the world's land and water resources for food and agriculture (SOLAW) – Managing systems at risk. Food and Agriculture Organization of the United Nations, Rome Routledge; Taylor and Francis Group, London.

FAO and ITPS. 2015. Status of the World's Soil Resources (SWSR) – Main Report. Food and Agriculture Organization of the United Nations and Intergovernmental Technical Panel on Soils, Rome, Italy.

Farage, P. K., Ardo, J., Olsson, L., Rienzi, E. A., Ball, A. S. and Pretty, J. N. 2007. The potential for soil carbon sequestration in three tropical dryland farming systems of Africa and Latin America: A modelling approach. *Soil & Tillage Research* 94, 457–72 https://doi.org/10.1016/j.still.2006.09.006.

Feng, S. and Fu, Q. 2013. Expansion of global drylands under a warming climate. *Atmospheric Chemistry and Physics*, 13: 10081–94.

Fischer, G., Shah, M., van Velthuizen, H. and Nachtergaele, F. 2006. *Agro-Ecological Zones Assessments – Reprinted from Encyclopaedia of Life Support Systems (EOLSS)*. EOLSS Publishers, Oxford, UK.

Glenn, E. P. and et al. 1999. Salt tolerance and crop potential of halophytes. *Critical Review in Plant Sciences* 18(2): 227–55. Doi: 10.1080/07352689991309207.

Goma, M. 2005. Participatory management of salt-affected soils in Egypt: Role of Executive Authority for Land Improvement Projects –EALIP. In *Promoting Participatory Management of the Land System to Enhance Soil Conservation* (P. Zdruli and G. Trisorio Liuzzi (Eds)). Workshop proceedings, Alexandria, Egypt. MEDCOASTLAND publication 3: 101–18, IAM Bari.

Hulme, M. 1996. Recent climatic change in the world's drylands. *Geophysical Research Letters* 23: 61–4.

ICARDA. 2012. Iraq salinity project: Salinity management in Central & Southern Iraq. Iraq salinity initiative: Assessment and solutions to reduce salinity in Iraqi agriculture. http://iraq.icarda.org/ [last accessed 3 February 2017].

ICARDA. 2015. Towards dynamic drylands. https://www.icarda.org/annual-report-2015/[last accessed 3 May 2017].

IFAD. 2016. The Drylands Advantage: Protecting the environment, empowering people https://www.ifad.org/documents/10180/e036916a-9d15-463f-8952-56d1566d7ac8 [last accessed 10 February 2017] based on source data from https://www.thegef.org and Asian Development Bank. 2010.

IPCC. 2014. Climate Change 2014: Synthesis Report Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, R. K. Pachauri and L. A. Meyer (Eds)]. IPCC, Geneva, Switzerland, 151p.

IUSS Working Group WRB. 2015. *World Reference Base for Soil Resources 2014, Update 2015*. International soil classification system for naming and creating legends for soil maps. World Soil Resources Reports 106. FAO, Rome.

Jenny, H. 1941. *Factors of Soil Formation. A System of Quantitative Pedology*. MCraw-Hill, New York.

Karlen, D. L., Mausbach, M. J., Doran, J. W., Cline, R. G., Harris, R. F. and Schuman, G. E. 1997. Soil quality: A concept, definition, and framework for evaluation. *Soil Science Society of America Journal* 61: 4–10.

Karlen, D. L., Goeser, N. J., Veum, K. S. and Yost, M. A. 2017. On-farm soil health evaluations: Challenges and opportunities. *Journal of Soil and Water Conservation* 72(2): 26A–31A. Doi: 10.2489/jswc.72.2.26A.

Kassam, A., Friedrich, T., Derpsch, R., Lahmar, R., Mrabet, R., Basch, G., González-Sánchez, E. J. and Serraj, R. 2012. Conservation agriculture in the dry Mediterranean climate. *Field Crops Research* 132: 7–17.

Kibblewhite, M. G., Ritz, K. and Swift, M. J. 2008. Soil health in agricultural systems. *Philosophical Transactions of the Royal Society B* 363: 685–701.

Laghari, M., Naidu, R., Xiao, B. and et al. 2016. Recent developments in biochar as an effective tool for agricultural soil management: A review. *Journal of the Science of Food and Agriculture* 96(15): 4840–9.

Laishram, J., Saxena, K. G. Maikhuri, R. K. and Rao, K. S. 2012. Soil quality and soil health: A review. *International Journal of Ecology and Environmental Sciences* 38(1): 19–37.

Lal, R. 2004. Carbon sequestration in dryland ecosystems. *Environmental Management* 33: 528–44. https://doi.org/10.1007/s00267-003-9110-9.

Lal, R. 2009. Sequestering carbon in the soils of arid ecosystems. *Land Degradation & Development* 20, 441–54 https://doi.org/10.1002/ldr.934.

Lal, R. 2015. Cover cropping and the '4 per Thousand' proposal. *Journal of Soil and Water Conservation*, 70: (6) 141A. Doi: 10.2489/jswc.70.6.141A.

Lal, R. 2016. Soil health and carbon management. *Food and Energy Security* 5, 212–22.

Laureano, P. 2001. *The Water Atlas: Traditional Knowledge to Combat Desertification*. Bollati Boringhieri editore s.r.l, Turin, 441p.

Le Quang, B., Biradar, C., Thomas, R., Zucca, C. and Bonaiuti, E. 2016. Socio-ecological context typology to support targeting and upscaling of sustainable land management practices in diverse global dryland. In 8th International Congress on Environmental Modelling and Software (S. Sauvage, J.-M. Sánchez-Pérez and A. Rizzoli (Eds.)). International Environmental Modelling and Software Society (iEMSs). http://www.iemss.org/society/index.php/iemss-2016-proceedings.

Lehman, R. M., Cambardella, C. A., Stott, D. E. and et al. 2015. Understanding and enhancing soil biological health: the solution for reversing soil degradation. *Sustainability* 7(1): 988–1027. Doi: 10.3390/su7010988.

Liniger, H., Mekdaschi-Studer, R., Hauert, C. and Gurtner, M. 2011. *Sustainable Land Management in Practice–Guidelines and Best Practices for Sub-Saharan Africa*. TerrAfrica. World Overview of Conservation Approaches and Technologies (WOCAT), Wageningen, The Netherlands; Food and Agriculture Organization of the United Nations (FAO), Rome, Italy.

Maghchiche, A., Haouam, A. and Immirzi, B. 2010. Use of polymers and biopolymers for water retaining and soil stabilization in arid and semiarid regions. *Journal of Taibah University for Science* 4: 9–16. http://dx.doi.org/10.1016/S1658-3655(12)60022-3.

Marques, M. J., Schwilch, G., Lauterburg, N., Crittenden, S., Tesfai, M., Stolte, J., Zdruli, P., Zucca, C., Petursdottir, Th., Evelpidou, N., Karkani, A., AsliYilmazgil, Y., Panagopoulos, Th., Yirdaw, E., Kanninen, M., Rubio, J. L., Schmiedel, U. and Doko, A. 2016. Multifaceted impacts of sustainable land management in drylands: A review. *Sustainability* 8: 177. Doi: 10.3390/su8020177.

Middleton, N. J. and Thomas, D. S. G. 1992. *UNEP: World Atlas of Desertification*. Edward Arnold, Sevenoaks.

Millennium Ecosystem Assessment. 2005. *Ecosystems and Human Well-being: Desertification Synthesis*. Chapter 22 Dryland Systems (by U. Safriel and Z. Adeel). World Resources Institute, Washington, DC.

Montanarella, L. 2015. Agricultural policy: Govern our soils. *Nature* 528: 32–3.

Mortimore, M. 2009. *Dryland Opportunities*. IUCN, Gland, Switzerland; HED, London, UK; UNDP, New York, USA

Mostafa, H. 2014. Effective moisture conservation method for heavy soil under drip irrigation. *Agricultural Engineering International: CIGR Journal* 16(2): 1–9.

Nunes, A., Oliveira, G., Mexia, T., Valdecantos A., Zucca, C., Costantini, E. A. C., Abraham, E., Kyriazopoulos, A. P., Salah, A., Prasse, R., Correia, O., Milliken, S., Kotzen, B., Branquinho, C. 2016. Ecological restoration across the Mediterranean Basin as viewed by practitioners. *Science of the Total Environment* 566–567:722–32 https://doi.org/10.1016/j.scitotenv.2016.05.136.

Oweis, T. and Hachum, A. 2006. Water harvesting and supplemental irrigation for improved water productivity of dry farming systems in west Asia and North Africa. *Agricultural Water Management* 80: 57–73. DOI:10.1016/j.agwat.2005.07.004.

Paustian, K., Lehmann, J., Ogle, S., Reay, D., Robertson G. P. and Smith, P. 2016. Climate-smart soils. *Nature*, 532: 49–57.

Peairs, F. B., Bean, B. and Gossen, B. D. 2005. Management implications of reduced fallow periods in dryland cropping systems in the Great Plains. *Agronomy Journal* 97: 373–88.

Previtali, F., Gasmi, N., Iulitta, F., Cantelli, D., Deroma, M., Madrau, S. and Zucca, C. 2014. The geomorphologic and pedo-morphologic maps of Skhirat (Feriana, Tunisia) at the 1:50,000 scale. *Journal of Maps* 10: 73–81. DOI:10.1080/17445647.2013.848420.

Rutherford, W. A., Painter, T. H., Ferrenberg, S., Belnap, J., Okin, G. S., Flagg, C. and Reed, S. C. 2017. Albedo feedbacks to future climate via climate change impacts on dryland biocrusts. *Nature Scientific Reports* 7: 44188. Doi: 10.1038/srep44188.

Scharlemann, J. P., Tanner, E. V., Hiederer, R. and Kapos, V. 2014. Global soil carbon: understanding and managing the largest terrestrial carbon pool. *Carbon Management* 5, 81–91.

Serraj, R. and Sidique, K. H. M. 2012. Conservation agriculture in dry areas. *Field Crops Research* 132: 1–6.

Sherwood, S. and Uphoff, N. 2000. Soil health: research, practice, and policy for a more regenerative agriculture. *Applied Soil Ecology* 15: 85–97.

Smith, P. Bustamante, M., Ahammad, H. and et al. 2014. Agriculture, Forestry and Other Land Use (AFOLU). In *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (Edenhofer, O. and et al. (eds.)). Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Soil Survey Staff. 2014. *Keys to Soil Taxonomy*, 12th ed. USDA-Natural Resources Conservation Service, Washington, DC.

Stabinsky, D. 2015. The French initiative '4 pour mille' (4‰) and soil carbon sequestration: oui, mais… Zennström Professorship in Climate Change Leadership, Working Paper 1. Uppsala University, Uppsala, Sweden; College of the Atlantic, Bar Harbor, Maine, USA.

Tejdor M., Jimenez C. and Diaz, F. 2007. Rehabilitation of saline soils by means of volcanic material coverings. *European Journal of Soil Science* 58(2): 490–5. http://dx.doi.org/10.1111/j.1365-2389.2007.00909.x.

Tondoh, J., Kone, A. W., N'Dri, J. K., Tamene, L. and Brunet, D. 2013. Changes in soil quality after subsequent establishment of Chromolaena odorata fallows in humid savannahs, Ivory Coast. *Catena* 101: 99–107. DOI:10.1016/j.catena.2012.10.005.

UNCCD.1. Article 1. http://www.unccd.int/en/about-the-convention/Pages/Text-Part-I.aspx [accessed 30 January 2017].

UNCCD.2. Decade for Deserts and the fight against Desertification. http://www.un.org/en/events/desertification_decade/value.shtml [accessed 30 January 2017].

UNEP, WMO, UNCCD. 2016. *Global Assessment of Sand and Dust Storms*. United Nations Environment Programme, Nairobi.

van Groenigen, J. W., van Kessel, C., Hungate, B. A. and et al. 2017. Sequestering soil organic carbon: A nitrogen dilemma. *Environmental Science & Technology* 51(9): 4738–9. DOI:10.1021/acs.est.7b01427.

Vetter, T., Rieger, A. K. and Nicolay, A. 2014. Disconnected runoff contributing areas: Evidence provided by ancient watershed management systems in arid northeastern Marmarica (NW-Egypt). *Geomorphology* 212: 41–57. DOI:10.1016/j.geomorph.2013.10.002.

Wall, D. H., Snelgrove, P. V. R. and Covich, A. P. 2001. Conservation priorities for soil sediment invertebrates. In *Conservation Biology. Research Priorities for the Next Decade* (Soule, E. and Orians, G. H. (Eds)). Island Press, Society for Conservation Biology, Washington DC, pp. 99–123.

Wall, D. H., Bardgett, R. D., Behan-Pelletier, V., Herrick, J. E., Jones, H., Ritz, K., Six, J., Strong D. R., Wim H. and van der Putten, W. H. 2012. *Soil Ecology and Ecosystem Services*. Oxford University Press, USA, p. 464.

Weil, R. R. and Magdoff, F. 2004. Significance of soil organic matter to soil quality and health. In *Soil Organic Matter in Sustainable Agriculture*, Chapter 1(F. Magdoff and R. R. Weil (Eds)). Boca Raton, CRC Press LLC, pp. 1–44.

Yirdaw, E., Tigabu, M. and Monge, A. 2017. Rehabilitation of degraded dryland ecosystems – review. *Silva Fennica* 51(1B): article id 1673. https://doi.org/10.14214 /sf.1673.

Zdruli, P. 2014. Land resources of the Mediterranean: Status, pressures, trends and impacts on regional future development. *Land Degradation & Development* 25: 373–84 https://doi.org/10.1002/ldr.2150.

Zdruli, P., Cherlet, M. and Zucca, C. 2017a. Mapping desertification: constraints and challenges. In *Encyclopedia of Soil Science*, Third Edition (R. Lal (Ed.)). Taylor&Francis. DOI:10.1081/E-ESS3-120052917.

Zdruli, P., Lal, R., Cherlet, M., Kapur, S. 2017b. New world atlas of desertification and issues of carbon sequestration, organic carbon stocks, nutrient depletion and implications for food security. In *Carbon Management, Technologies, and Trends in Mediterranean Ecosystems*. *Volume 15 of the Series The Anthropocene: Politik – Economics – Society – Science* (S. Erşahin, S. Kapur, A. Erhan, A. Namlı and H. E. Erdoğan (Eds)). Springer, pp. 13–25. DOI: 10.1007978-3-319-45035-3_2.