# 6 Drylands

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## Abstract

Drylands are characterized by physical water scarcity, often associated with land degradation and desertification. Other factors that contribute to these problems include high population densities, unwise agricultural practices and overgrazing. However, while desert ecosystems are fragile and vulnerable and can collapse in the short term, given the right conditions and protection, these areas also have a great potential for recovery. Examples of the recovery of areas have led to the formation of counter paradigms and the emergence of a new understanding of drylands. This new understanding is founded on the recognition of the variability of these ecosystems from place to place and year to year, and of the influences of desert plants, animals and the agricultural practices of the people who live in drylands. This chapter defines both old and new paradigms, and discusses conditions that lead to non-sustainable situations and vulnerabilities. In addition, strategies are considered that can lead to proper land use and recovery.

## Background

Drylands are arid and semi-arid areas where evapotranspiration exceeds rainfall for some part of the year but where there are still opportunities for livestock raising and seasonal cropping. These lands are found on all continents and include roughly all of the Middle East, half of India and about 70% of Africa (including the millet-based Sudano–Sahelian zone, the maize–groundnut belt of southern Africa and the Maghreb). There is evidence to support the idea that the actual land mass that can be considered arid or semi-arid is growing (UNCCD, 2010). Physical water scarcity, probably the most prominent constraint in drylands, is worsening, with per capita water flows reduced by many biophysical and social factors. This physical water scarcity is tied to reduced rainfall intensity, uneven distribution of rainfall with frequent drought cycles, and poor soil water holding capacity of the

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landscapes. Water scarcity for agriculture is also due to poor water management and poor agricultural practices that lead to low soil moisture contents, low plant productivity, low nutrient availability and poor soil development. In turn, this results in a relatively high susceptibility to soil erosion, salinization and land degradation in general (Millennium Ecosystem Assessment, 2005; Chapter 4).

Physical water scarcity in drylands is mostly linked to climate variability and recurrent droughts, which cause variations in primary production. Climate change, together with decreasing amounts of rainfall and increasing rainfall variability (Burke *et al*., 2006), is believed to exacerbate these constraints, especially for those who do not have secure access to irrigation water. High population growth rates in drylands, especially in the tropics, has led to land use changes in the entire watershed – from the water towers (mountain areas) to the lowlands – that might trigger land degradation if supportive institutional and sociopolitical mechanisms are not present.

## Challenges

Desertification, defined as resource (land, water, vegetation, biodiversity) degradation, is a major environmental problem in drylands, impairing various ecosystem services. It is related to the inherent vulnerability of the land and is caused by a combination of social, economic and biophysical factors, operating at varying scales. The direct effects of desertification include soil nutrient losses, decreased infiltration and soil water holding capacity, and impaired primary productivity. These, in turn, result in changes in the species of plants and animals that can survive in the area, as well as in the disruption of various ecosystem services, including nutrient cycling, water regulation and provision, and climate regulation (Millennium Ecosystem Assessment, 2005). Biodiversity, which is key to the provision of various dryland ecosystem services, decreases as a result of land degradation. According to the desertification paradigm, which is based on the assumption that natural systems are in a state of equilibrium that can be irreversibly disrupted (Millennium Ecosystem Assessment, 2005), desertification leads to a downwards spiral of productivity loss and increasing poverty.

However, evidence of recovery in areas that were previously thought to be irreversibly degraded, e.g. the greening of the Sahel (Herrmann *et al*., 2005; Olsson *et al*., 2005), has led to the emergence of counter-paradigms. Some argue that dryland agroecosystems are better described as non-equilibrium systems, in which considerable variability from place to place and from year to year is common, and related to irregular events, such as droughts, that impede the establishment of stable states (Ellis and Swift, 1988; Behnke *et al*., 1993). Others suggest that 'triggers' must be found in order to enable the rapid rehabilitation of degraded areas. For example, in northern Uganda, Mugerwa (2009) found a solution for overcoming the tendency for termites to keep degraded rangelands in a state of non-productivity. There is an emerging consensus that both dryland ecology (Scheffer *et al*., 2001; Washington-Allen and Salo, 2007) and people's livelihoods (Folke, 2006) in dry areas respond to key drivers of change in a non-linear way, so that systems have multiple states displaying some sort of stability, which are separated by thresholds. State and transition models (Stringham *et al*., 2003) have begun to replace models based on equilibrium concepts, and diagnostic tools for detecting thresholds using remote sensing are being developed and applied (Washington-Allen *et al.,* 2008).

The main objective of sustainable agriculture in drylands is to produce crops and feed livestock in a manner that utilizes the limited water resources efficiently, without applying harmful methods of cultivation and without overgrazing or otherwise endangering fragile marginal lands. Conventional agriculture from milder climates that requires expensive inputs to produce fruits and vegetables is rarely sustainable in arid zones. In fact, conventional water-intensive agricultural methods in arid zones may deplete water resources beyond their recovery capacity, sometimes until the resources are no longer usable, and greatly contribute to soil loss by water and wind erosion. Vegetation depletion, the loss of potentially valuable species of plants, and the loss of fertility and productivity in marginal lands under cultivation are also contributing factors.

Therefore, more appropriate approaches for drylands must be applied, based on both cultivating and protecting dryland agroecosystems. Examples include the replanting of degraded areas with useful plants that are tolerant or resistant to drought and salinity, cultivation in soil and water-thrifty modes, or managing grazing and water collection areas with an eye to conservation and future use. The greening of the Sahel after successive droughts was attributed partly to increased rain but also to widespread adoption of sustainable farming practices, such as the laborious planting of windbreaks and shelterbelts, the establishment of resilient plants and field texturing (such as making contour bunds and ditches) (Herrmann *et al.*, 2005; Reij *et al.*, 2005, 2009).

With increasing population pressure, traditional agriculture may no longer be sufficient to maintain the productivity of arid ecosystems. Sustainable agriculture in arid and saline areas must thus be based on an integrated approach that maximizes technical opportunities for the development of specifically desert-adapted crops, soil fertility improvement, protecting fragile desert soil, integrating local crops and animals, and mobilizing underutilized water sources. Employing rainwater management strategies at plot, farm and landscape scales is a valid entry point for rehabilitating the vegetation and improving the productivity of these dryland systems, especially if soil storage systems can also be employed. The synergy of such a combined strategy will greatly increase the use efficiency of the resource base. The expert use of local inputs, local knowledge and indigenous crops, utilized with an eye to the conservation of desert soil and the thrifty use of all appropriate water resources, can enhance local agricultural systems and increase their ability to support local people (both women and men).

Such an approach would not preclude the cultivation of livelihood crops or plough agriculture but would integrate the conventional crops into rotations and reclamation projects to allow greater sustainability (Kirkby *et al.*, 1995). Protecting degraded landscapes from direct contact with livestock and people for a limited period of time has been found to be an effective strategy for returning landscapes to productivity in Ethiopia (Amede *et al.*, 2011; see also Box 9.1 in Chapter 9). In addition, a broader approach to agroecosystem management increases the options for livelihoods and employment at the local level, especially for women, by creating opportunities for trade and processing, and by increasing the amount of usable materials for the dryland household.

The enhancement of existing farming systems or the introduction of new ones requires the integration of the different needs, interests and perceptions of local male and female farmers, particularly of marginal groups who are more vulnerable to environmental degradation. These management strategies also seek collective action at community and higher levels to facilitate the interaction of system components and to combine production with sustainable resources management. The successful experiences of the Globally Important Agricultural Heritage Systems (GIAHS) initiated by FAO (Food and Agriculture Organization of the United Nations) in 2002 in the drylands of Morocco, Italy and the USA demonstrate the importance of global support to local indigenous knowledge systems in preserving the productivity of these arid landscapes (GIAHS, 2013). Agricultural changes might trigger different impacts on the livelihoods of men and women, and on small and large landholders, whose diversity needs to be taken into account. New crops, new technologies and external inputs such as soil fertilization may be required to optimize the agroecosystem and produce food sustainably. Where feasible, these approaches can be fitted carefully around traditional agricultural practices to make more water available, including through the development of groundwater resources, which can lead to the synergistic integration of agriculture, animal husbandry, conservation planting and agroforestry.

## Dryland Soil Management

Topsoil is a resource that is formed and renewed very slowly in drylands. Low levels of macronutrients, nitrogen, phosphorus and potassium are not a problem unless the soil surface has been lost (Bainbridge, 2007), but nutrients are often concentrated in the top 2–3 cm of desert soil. Newly cultivated dryland soils often produce a sudden and one-time flush of fertility, setting an excellent crop, but as the accumulated organic material is used up, the nutrients are depleted and the soil becomes compacted, and further yields are usually disappointing.

A specific risk in drylands is the development of impermeable clay crusts when the clay, which is normally dispersed throughout the soil profile, is dissolved by excess water and floats to the top when water pools; later, when the water evaporates, the clay hardens in the sun to hard ceramic-like plates on the soil surface. Compaction and disturbance, as happens with frequent ploughing, also reduce the populations of beneficial soil organisms. The total numbers of fungi, bacteria and nematodes tend to be much lower in disturbed soils, while pathogens are more common and the soil regenerative influences of ant and termite colonies are greatly reduced.

Without sufficient protective land cover, wind erosion can move vast quantities of soil away and up into the air, causing choking storms, burying plants and crops, and contaminating food and water (there is more on land degradation and soil erosion in Chapter 4). Entire communities can disappear in eroded dryland areas under layers of sand and dust, as happened in the infamous Dust Bowl in the USA in the 1930s, and in the serious and ongoing encroachment of the sands of the Gobi Desert on to agricultural land in China.

With adequate management, it is possible to build up and protect topsoil and so enhance the supporting and regulatory services of the ecosystem, e.g. nitrogen can be increased by the planting of nitrogen fixing trees and legumes, and by the utilization of manure. Such ecological practices can help to prevent and reduce erosion. Available potassium is increased with the breakdown of plant materials, especially leaf litter. Phosphorus in desert soils is often bound up in unusable forms, and the nutrient is released only by biological activity in the soil. The application of organic fertilizers such as manure and compost can increase the soil's water holding capacity in addition to providing plant nutrition.

The strategies that best address the problems of erosion are those that lessen the force of the wind, combined with techniques that slow and hold the water so that it can be used to stimulate vegetation. Both water and wind erosion can thus be addressed by approaches that entail a certain amount of field texturing and the planting of especially hardy types of plants and trees. Techniques like these have also been proposed as part of an ecosystem approach to land and water management in the Tana River Basin in Kenya, particularly in the drier middle catchment (Knoop *et al*., 2012).

Soil building can be enhanced by improved nutrient cycling (see Chapter 4), particularly through improved crop–livestock linkages and reclamation plantings that encourage soil microorganisms. The rational use of combined interventions from modern and traditional desert agriculture can offer new ways to cultivate the desert in a sustainable manner.

## Mobilizing Water in Drylands

In an effort to supply the needs of the populations in drylands for water, food and produce, various forms of rainwater management practices have been initiated in several countries (e.g. Ngigi, 2003; Vohland and Boubacar, 2009). For instance, traditional 'tanks' in South Asia, small water harvesting structures in West Africa (zai pits, small reservoirs), soil and water conservation practices in Ethiopia, and groundwater use in Southern Africa are examples of cases where improved water management practices are bringing about change in people's livelihoods. Runoff, wastewater (including grey and black water, treated and untreated) and saline water resources are being used for farming (see Box 6.1). Saline or brackish water, often of a quality that precludes drinking, is a commonly underutilized water resource in many areas, although it can only be used for carefully selected crops, and in agricultural strategies such as the cultivation of halophytic annuals or perennials, or local grass or green manure crops that are salt tolerant. In areas lacking

**Box 6.1.** Examples of water collection in arid areas

Runoff water can be directed after collection, via a division box, to lateral canals, especially across the face of a slope to allow for storage in that slope, or it can be directed into small depressions or ditches in more level areas (Knoop *et al.*, 2012). These features can be produced by hand labour with simple tools. Both slopes and ditches can be planted with perennials that have low water use and heavily mulched to prevent evaporation. Water can also be stored in contour bunds or grass strips by directing it into loading ditches on the upslope side of the features. A strip planted with grass or a fodder crop will wick the water laterally across its face, while an elevated planted bed formation will absorb the water upwards into its core. A sound combination of interventions could also help to protect against wind and water erosion.

These principles have been applied in a rainwater harvesting project managed by The Arava Institute for Environmental Studies (AIES) in the Negev, Israel. Nir Moshe, with an average annual rainfall of 250 mm, is the site of AIES's largest rainwater collection experiment in the Negev. This project has 20,000 $m^2$ of contour bunds planted with drought-tolerant trees, and contour furrows that collect rainwater from a series of nearby slopes. A pond has been created at what was once the lowest point of a gully caused by erosion by closing the gully at one end, and then gravelling and lining it so that it can accommodate several thousand cubic metres of water. By the end of January 2010, after one winter in operation, 2,500,000 l of water had been collected on this site by the catchment furrows and stored in tree-covered bunds. The runoff water was drained into the small pond. This rainwater harvesting system feeds an agroecosystem that provides a range of provisioning (food, fodder and other products from the trees), regulatory (water and erosion regulation) and supporting (nutrient cycling) ecosystem services.

reservoir sites or ponds for natural water storage, soil-based storage of moisture is an interesting possibility and can be done by, for example, improved *in situ* water management and groundwater recharge (Johnston and McCartney, 2010; McCartney and Smakhtin, 2010).

The use of wastewater in agriculture is a common practice in many countries, often in response to water shortages or changes in water supply and demand, or because traditional sources of irrigation water have been polluted with effluent. Estimates of wastewater use vary, not least because there is no agreed classification system, but some 23 countries use untreated wastewater, 20 use treated wastewater and a further 20 use both types of wastewater (Jiménez *et al.*, 2010). FAO estimates that wastewater is used on 10% of all irrigated land (FAO, 2009; Winpenny *et al.*, 2010). Much of the planned use of treated wastewater irrigation is currently in arid areas, for example Israel, which is a world leader in reclaiming more than 60% of its sewage effluent (Hamilton *et al.*, 2007). Furthermore, Scott *et al.* (2010) estimate that the area that uses wastewater informally is ten times larger than that which uses it formally (Drechsel *et al.*, 2011).

The drivers of wastewater irrigation are complex, but they include access to a secure, year-round source of water (as well as nutrients) that allows farmers to irrigate in the dry season and supplement their incomes. In some cases, wastewater use has arisen because the supply of traditional water resources, such as canal water in Pakistan, has diminished over the years (Weckenbrock *et al.*, 2011) or have become polluted. The result is that wastewater use is an important part of agricultural production throughout the world and it should be considered as a legitimate component within an integrated water resource management approach.

However, concern about the risk to public health makes wastewater use a controversial issue and may limit its planned extension (see Chapter 5). Guidelines on wastewater use in agriculture typically stipulate treatment levels and processes, although in 2006 the World Health Organization (WHO) published guidelines that utilize a risk management approach and recommend the introduction of barriers to risks along the pathway from wastewater production to crop consumption (WHO, 2006). This offers a pragmatic and workable solution that is designed to protect farmers as well as consumers.

## Sustainable Crop Selection for Drylands

Because of the extreme aridity of many of the areas under discussion, water is most efficiently used on plants that can become multifunctional features in the landscape, as part of a new ecosystem. Every plant is then a multi-purpose species, capable of breaking the force of the wind and absorbing water, but also of producing food, fruit, oil, fodder and firewood, and of fixing nitrogen, hosting useful or edible insects, or providing building material, hence providing a multitude of ecosystem services. Cultivating a diverse and sustainable crop repertoire would support livelihoods at the local level by making dryland agroecosystems more productive and sustainable, thus increasing the amount of usable materials for the desert household.

An investigation of local plants in each candidate site helps to identify suitable plants, i.e. which local plants may be a valuable source of food for the human population, which can be utilized to support the flocks and herds, and those that may be necessary for the restoration of water and nutrient cycling in the most degraded areas (Bainbridge, 2004). Many suitable crops might be found among the local perennial plants (Shmida and Darom, 1992). Perennial plants and their longer cycles of living and yielding are much more suitable to the desert than annual or seasonal crops as they need little tillage and are more water thrifty. Being adapted to the slow breakdown of organic matter and release of minerals in dryland soils, such perennials allow for natural regeneration of soil structure, while each litre of water invested in a perennial is converted to long-lived plant tissue, fruit, seeds and leaves (Solowey, 2010).

As an example, Table 6.1 lists several local crop candidates from a zone of hyper-aridity shared by Israel and Jordan, which can be grown in areas with 50 to 120 mm of rainfall utilizing water harvesting technologies. Some of these plants were introduced from other drylands to Israel and Jordan through cooperative programmes between the Arava Institute for Environmental Studies and the Jordan University of Science and Technology. Others are wild plants undergoing an accelerated process of domestication. The advantages of using such desert-adapted plants include the water-thrifty nature of the germplasm, the availability of fresh genetic material with no need for quarantine, local knowledge, and familiarity relative to the plant material and possibly existing systems for utilization of the plant products. All plants in Table 6.1 are physiologically appropriate for arid and hyper-arid areas, i.e. drought-resistant, and multipurpose, i.e. producing food and material for sale and trade. The plants were selected because of their tolerance for high pH soil and their physical influences in various cultivation formats, which enable them to improve the organic matter content of poor soils and soil permeability. Their medicinal value and their value as browse and feedstock were also taken into account. Many of these plants could support small-scale value-added product manufacture.

Perennial plantations, which ideally are made up of various species, such as in most oases, are regeneration friendly. They may make best use of the available water and may help to generate supporting and regulatory ecosystem services. Trees shade and protect the soil from the sun, lowering soil temperatures and thereby regulating the microclimate. Fallen leaves produce natural mulch and encourage colonization by beneficial soil organisms. Trees and perennial plants are sanctuaries and nesting places for birds, hunting grounds for insectivores and feeding areas for pollinating insects. Their roots are highways into the earth for ants, beneficial nematodes, beneficial fungi and mycorrhizae, as well as conduits for sparse and precious rainfall.

When perennial plantations are established, their mitigating presence allows for the integration of some annual plants to utilize the runoff from irregular rains. Perennial trees can thus be combined with annual elements to enhance biodiversity and provide multiple benefits (Solowey, 2010). The annual plants may include grass for grazing, medicinal herbs for personal use or cottage industry, and leafy vegetables to improve the diet of the farmer and herder. Hence, a balanced agroecosystem can be established, with a wealth of regulatory and supporting ecosystem services, safeguarding the delivery of food and other provisioning services. In semi-arid areas, well-managed rangelands or arboreal pastures

**Table 6.1.** Crop candidates and the potential contributions of their germplasm to ecosystem services in a desert area shared by Israel and Jordan. Plants not native to Israel and Jordan are in bold.

| Crop candidate | Provisioning services | Regulatory services[a] | Supporting services[b] |
|---|---|---|---|
| *Acacia* | Sap, pods, wood, browse | Xerophyte, apiary | Pioneer |
| *Achillea* | Essential oil, flowers, medicinal | Apiary | Pioneer |
| ***Argania spinosa*** | Nuts, oil, wood, poles, browse | Apiary | Reclamation |
| *Artemisia* spp. | Essential oil for medicinal use (antimalarial) | Apiary | |
| *Atriplex* spp. | Flowers, pasture, medicinal | Apiary | |
| *Balanites* spp. | Fruit, oil, flowers, sap, leaves, medicinal, poles, fence, browse | Shade | |
| ***Boswellia* spp.** | Sap, incense, wood for smoking, medicinal | Apiary | Reclamation |
| ***Capparis spinosa* (capers)** | Buds, medicine, cosmetics, liquor | Apiary | Ground cover |
| *Cassia* spp. | Flowers, leaves, pods | Apiary | Ground cover, reclamation |
| ***Commiphora* spp.** | Sap, wood for smoking, flowers, medicinal | Xerophyte, apiary | Reclamation |
| *Haloxylon* spp. (saxaul) | Browse, sap, flowers | Dune stabilization | Reclamation |
| *Pistacia terebinthus* (terebinth) | Resin, wood, browse, rootstocks | Shade, windbreak | Reclamation |
| ***Prosopis* spp.** | Browse, wood, poles, pods | Stabilization, apiary, windbreak | Reclamation |
| *Salicornia* spp. (glasswort) | Browse, flowers, oil | Apiary | Reclamation, pioneer |
| ***Sclerocarya birrea* (marula)** | Fruit, oil, timber, liquor, browse | Shade | Reclamation |
| *Ziziphus* spp. | Fruit, poles, liquor, juice, browse | Living fence, windbreak | |
| *Zygophyllum* spp. | Browse, sap, flowers, pasture, medicinal | | Pioneer |

[a] Apiary plants are important habitats for bees, and hence contribute to pollination. Shade plants and windbreaks play a role in climate regulation. Xerophytes use very little water so help to regulate water flows. Living fence and (dune) stabilization are important in erosion regulation.

[b] Reclamation plants and ground cover help soil formation and nutrient cycling. Pioneer plants contribute to the mitigation of climate change.

could have similar impacts (see below). The perennial trees would ideally be multi-purpose, providing fruits, shade, fodder, wood and more. A good example of such a multi-purpose tree is the lalob – one of many common names (*Balanites aegyptiaca*), which supplies browse for goats and camels, fruit pulp for fermentation, medicinal sap, oil of good quality for illumination and firewood; it can also serve as an anti-erosion plant (National Research Council, 2008).

Another interesting example of a multi-purpose tree is the argan (*Argania spinosa*) of southern Morocco, which produces hardwood for tool manufacture when coppiced, can be a source of browsing for goats, a source of nectar and pollen for honey bees and an anti-erosive tree in areas with seasonal flooding but, most of all, is a source of edible oil, soap and cosmetic oil for the local people. For example, argan oil is used very much like olive oil in the Moroccan kitchen; it is also added to a porridge-like dish (semetar), and the roasted nuts are used to make argan nut butter (amalou) after extraction of the oil (Morton, 1987). Internationally, argan oil has become increasingly popular for cosmetic use on skin and hair, and there are claims that it benefits local livelihoods as well as the environment. While it does indeed seem to have a poverty-reducing impact and aid increased access to education for girls, the argan forest itself may now be under even more threat than it was before (Lybbert *et al.*, 2011).

Members of the *Prosopis* family of trees are all nitrogen fixers, as well as being multi-purpose trees. These trees can supply browse, high-quality protein food from pods, firewood, syrup and non-gluten flour for human consumption, shade and shelter for flocks, and building materials; they can also be used as windbreaks (Knoop *et al.*, 2012). In the dry season especially, the trees provide high-quality feed for livestock. Unfortunately, several *Prosopis* species have a tendency to invasiveness that needs to be carefully managed; they also need to be thinned to allow for the planting or emergence of other species. Introduced species should always be evaluated for weedy properties (Solowey, 2003).

## Grazing in Drylands

Dry rangelands support about 50% of the world's livestock population (Millennium Ecosystem Assessment, 2005) and are of huge importance for the often poor livestock keepers in these regions. The most important livestock production systems in dry areas are grazing systems, which occupy 77% of the dryland area worldwide; these are followed by mixed rainfed systems, with a share of 17%. Livestock-dominated and mixed crop–livestock systems in drylands cover about 11.9 and 6.9 million km$^2$, respectively, or about 15% and 9% of the 80.8 million km$^2$ comprising Latin America, Africa and South and South-east Asia (Thornton *et al.*, 2002; Table 6.2). In 2002, livestock-dominated areas were home to about 116 million people, whereas about 595 million people resided in mixed crop–livestock systems.

**Table 6.2.** Distribution of land and people in mixed crop–livestock and livestock dominated systems in drylands in developing countries (based on Thornton *et al.,* 2002).

| | Livestock-dominated systems | Mixed crop–livestock systems |
|---|---|---|
| Land area (million km$^2$) | 11.9 | 6.9 |
| Land area as % of country | 15 | 9 |
| Number of people (million) | 116 | 595 |
| Density (people/km$^2$) | 9.7 | 86.2 |

Herding can be viewed as a form of water harvesting in the sense that grazing animals capture the benefits of sparsely distributed rainfall by grazing pastures (Bindraban *et al*., 2010). Mobility is the primary and requisite characteristic of pastoral agroecosystems. Grazing by domestic and wild ungulates is the means of maintaining extensive grasslands that provide important ecosystem services, including the maintenance of biodiversity and carbon sequestration. At the same time, extensive cattle enterprises have been responsible for 65–80% of the deforestation of the Amazon at a rate of forest loss of 18–24 million ha/year (Herrero *et al*., 2009).

In recent decades, the expansion of cultivation and the establishment of international boundaries and barriers across traditional migratory routes have diminished mobility, forcing herders towards a more sedentary livelihood strategy that has often resulted in severe land and water degradation, aggravated poverty, poor health and food insecurity. The importance of rangelands for livestock grazing is highest in the arid agroecosystems, whereas in the semi-arid and sub-humid areas, grasslands are being converted into shrublands and cultivated land (Millennium Ecosystem Assessment, 2005). Small areas of encroaching cultivation can have a multiplier effect and reduce livestock production over much larger land areas. In arid regions, the expansion of cropland, inappropriate grazing practices (Geist and Lambin, 2004) and newly imposed barriers to the mobility of pastoralists may even increase trends in desertification. Policies directed to making nomads sedentary often have adverse effects as they reduce the traditional ability of pastoralists to respond to climate shocks, resulting in a downward spiral of poverty, conflict and social exclusion (de Jode, 2010).

In the tropics, the expansion of croplands at the expense of grazing areas is driven by increasing human populations (Kristjanson *et al*., 2004). As a result, in the sub-humid and semi-arid tropics, traditional pastoral practices are often being replaced with agropastoralism and mixed farming in which livestock increasingly depend on crop residues as feed. The transition from grazing to agropastoralism to mixed crop–livestock production is often accompanied by the migration of people, and an increased human population also puts enhanced pressure on fuel sources such as charcoal, further aggravating land degradation. Increased migration of people may lead to conflicts over access to natural resources, such as water resources, that are used by livestock keepers for drinking but also claimed by farmers for irrigating their crops. However, the increased interaction between pastoralists and farmers may lead to increased exchanges and closer collaboration too (Turner, 2004).

Inappropriate livestock grazing practices are often seen as the culprit causing rangeland degradation and desertification (Asner *et al*., 2004). Traditional pastoral practices are generally well adapted to make use of the spatially and temporally variable feed resources in rangelands (IIDE and SOS Sahel UK, 2010), but when these are disrupted or pressured as a result of demographic, climate or land use changes, livestock grazing may threaten the provision of ecosystem services. Overgrazing is a leading cause of land degradation in arid drylands, tropical grasslands and savannas worldwide. It leads to soil compaction, reduction in long-term grazing productivity, loss of topsoil, disruption of the hydrological cycle and deterioration of water quality. In such degraded rangelands, most water is lost as runoff and unproductive evaporation, so that water use efficiency is dramatically reduced. Increased runoff and the trampling of the soil by livestock lead to erosion and thence to siltation of downstream freshwater resources. This may lead to soil and vegetation degradation, reduced productivity and, eventually, food insecurity (Asner *et al*., 2004).

Although reports from drylands often paint grim pictures of poverty, drought and conflicts over resources, the degradation of drylands could be avoided by intensifying agricultural production and safeguarding pastoral mobility (Millennium Ecosystem Assessment, 2005). Options for carbon storage could be enhanced, as, because of their large area, rangelands could be a global sink of a roughly similar size to forests (Herrero *et al*., 2009; Box 2.3, Chapter 2). There is a real need for research on how this large potential can be tapped through technologies and policies for carbon sequestration. Rangelands could even be the source of significant regional increases in water productivity by judiciously using them as a feed source, at the same time as taking care to avoid overgrazing (Herrero *et al.*, 2009; Bindraban *et al.*, 2010).

Solutions for breaking the downward spiral of over-exploitation, degradation and disrupted ecosystem services in drylands should take on board the technical, sociopolitical and institutional issues that are involved (Amede *et al.*, 2009). Such solutions should secure property rights, be risk averse and take into account the labour constraints of women, men and children, as well as enabling their access to input and output value chains and market information (FAO *et al.*, 2010). In particular, securing the mobility of herds for access to natural resources, trade routes and markets is essential to avoid degradation and conflict (de Jode, 2010). This can be achieved through appropriate policies that take into account transboundary herd movements but also enable the creation of corridors and the establishment of water points and resting areas along routes. The strategic positioning of drinking water points helps to avoid the concentration of too many animals around one watering point, which would cause soil and vegetation degradation and water contamination (Brits *et al.*, 2002; Wilson 2007), and is instrumental in balancing feed availability with livestock numbers so that feed resources can be used optimally (Peden *et al.*, 2009).

Rangelands can be improved by changing them into arboreal pastures, using appropriate multifunctional perennial and annual species. The animals play their own role in the establishment, survival and distribution of plant species. Most herbivores prefer soft, fast-growing plants, so these disappear first. More resinous, nasty-tasting, spiny or tough plants – often the typical desert species – are eaten more slowly. Thus, grazing animals have their own impact on water availability, with wild herbivore populations fluctuating dramatically in response to rain and vegetation (Bainbridge, 2007), whereas domesticated livestock can survive and maintain herd size by feeding on cultivated perennial grasses and trees. Trees in grazing areas help to mitigate the impacts of the wind and water erosion that are rampant in degraded drylands. Planting arboreal pastures may also reduce competition between local animal herders over the rights to graze sheep and goats on the little bits of remaining vegetation.

Arboreal pastures are often suitable for reclaiming and using the wastewater and runoff that are currently damaging factors and turning them into water resources for the deliberate increase of native vegetation, so that the land degradation process is reversed. The ultimate goal is an increase of vegetation for grazing, the establishment of partnerships for sustainable grazing sites between former rivals and, it is hoped, the creation of examples that can be emulated in other contested, arid and desolate grazing areas to the benefit of all stakeholders (Evenari *et al.*, 1982). Arboreal pasturage can, therefore, provide a wide range of ecosystem services in addition to grazing grounds, such as erosion control and enrichment of the soil by leaf litter and from the nitrogen fixation that is done by appropriate tree species (Rabia *et al.*, 2008).

## Conclusions

Agriculture and pastoralism in drylands are challenged by the scarcity of various natural resources, in particular water and soil fertility. These conditions require site-specific solutions that include seeking synergies between agriculture and anti-desertification efforts. Degraded lands could be brought back under productive use through rangeland conservation and better farming practices, which, in turn, restore surface vegetation and soil functions, in particular water retention. New technologies, new cultivars and enhanced utilization of water resources can thus be combined to strengthen ecosystem services and increase water efficiency for the cultivation of suitable crops and modified rangelands. Strategies for more sustainable models of arid land agriculture include the efficient collection of runoff, soil-based storage of moisture and nutrients, and strategic planting of local and desert-adapted cultivars to increase the resource base and the provision of ecosystem services. When combined with organic fertilizers that increase the water-holding capacity of the soil, effective weed control and crop protection against pest and diseases, productivity under semi-arid conditions can triple or more and hence make more effective use of rainwater (Bindraban *et al*., 1999).

In semi-arid rangelands, providing incentives to livestock herders can help to improve herd management and safeguard the regulation and support of ecosystem services. These strategies must take into account the differentiated needs and capacities of local men and women and of different social groups, in this manner ensuring that those responsible for certain tasks are effectively able to accomplish them.

Such approaches are not necessarily technically complex, but they do require a wholesale shift towards more integrated approaches to agroecosystem management, building on the common goal of sustainability. They also require the building of institutional capacity and collective action to facilitate adoption and dissemination of these good practices in drylands. Looking at water, ecosystem and human needs in parallel, and identifying and building upon mutually supportive approaches, is the key, as is looking across sectors. By linking and combining appropriate production systems in a landscape, synergies can be explored. Drought-resistant plants, arboreal pastures and perennial grasses can be cultivated in a landscape with strategically placed corridors and water points for herds, thereby providing more sustainable exploitation options for agropastoralists. The integration of crop, tree, livestock and, in some cases, aquaculture, can enhance resource recovery and the reuse of resources for feed or soil fertility.

## References


Amede, T., Geheb, K. and Douthwaite, B. (2009) Enabling the uptake of livestock-water productivity interventions in the crop–livestock systems of sub-Saharan Africa. *The Rangeland Journal* 31, 223–230. doi:10.1071/RJ09008

Amede, T., Tarawali, S. and Peden, D. (2011) Improving water productivity in crop livestock systems of drought prone regions. Editorial Comment. *Experimental Agriculture* 47, 1–6.

Asner, G.P., Elmore, A.J., Olander, L.P., Martin, R.E. and Harris, A.T. (2004) Grazing systems, ecosystem responses and global change. *Annual Review of Environment and Resources* 29, 261–299. doi:10.1146/annurev.energy.29.062403.102142

Bainbridge, D.A. (2004) The anatomy, physiology, psychology and economics of desert destruction and restoration. Paper presented to: *3rd Mojave Desert Science Symposium, November 16–18, 2004, University of Redlands, California*.

Bainbridge, D.A. (2007) *A Guide for Desert and Dryland Restoration*. Island Press, Washington, DC.

Behnke, R.H. Jr, Scoones, I. and Kerven, C. (eds) (1993) *Range Ecology at Disequilibrium: New Models of Natural Variability and Pastoral Adaptation in African Savannas*. Overseas Development Institute, London.

Bindraban, P.S., Verhagen, A., Uithol, P.W.J. and Henstra, P. (1999) *A Land Quality Indicator for Sustainable Land Management: The Yield Gap*. Report 106, Research Institute for Agrobiology and Soil Fertility (AB-DLO), Wageningen, the Netherlands.

Bindraban, P., Conijn, S., Jongschaap, R., Qi, J., Hanjra, M., Kijne, J., Steduto, P., Udo, H., Oweis, T. and de Boer, I. (eds) (2010) *Enhancing Use of Rainwater for Meat Production on Grasslands: An Ecological Opportunity Towards Food Security. Proceedings 686, International Fertiliser Society, Cambridge, 10 December 2010, Leek, UK*. ISRIC World Soil Information, Wageningen, the Netherlands.

Brits, J., van Rooyen, M.W. and van Rooyen, N. (2002) Ecological impact of large herbivores on the woody vegetation at selected watering points on the eastern basaltic soils in the Kruger National Park. *African Journal of Ecology* 40, 53–60. doi:10.1046/j.0141-6707.2001.00344.x

Burke, E.J., Brown, S.J. and Christidis, N. (2006) Modeling the recent evolution of global drought and projections for the twenty-first century with the Hadley Centre climate model. *Journal of Hydrometeorology* 7, 1113–1125. doi:10.1175/JHM544.1

de Jode, H. (ed.) (2010) *Modern and Mobile. The Future of Livestock Production in Africa's Drylands.* International Institute for Environment and Development (IIED), London and SOS Sahel International UK, Oxford, UK.

Drechsel, P., Cofie, O.O., Keraita, B., Amoah, P., Evans, A. and Amerasinghe, P. (2011) Recovery and reuse of resources: enhancing urban resilience in low-income countries. *Urban Agriculture Magazine* 25, 66–69.

Ellis, J.E. and Swift, D.M. (1988) Stability of African pastoral ecosystems: alternate paradigms and implications for development. *Journal of Range Management* 41, 450–459.

Evenari, M., Shanan, L. and Tadmor, N. (1982) *Negev: The Challenge of a Desert*, 2nd edn. Harvard University Press, Cambridge, Massachusetts.

FAO (2013) Municipal wastewater: from production to use (with link to the AQUASTAT database). Food and Agriculture Organization of the United Nations, Rome. Available at: http://www.fao.org/nr/water/aquastat/wastewater/index.stm (accessed February 2013).

FAO, IFAD and ILO (2010) *Gender Dimensions of Agricultural and Rural Employment: Differentiated Pathways out of Poverty. Status, Trends and Gaps*. Food and Agriculture Organization of the United Nations, Rome, International Fund for Agricultural Development, Rome and International Labour Organization, Geneva, Switzerland.

Folke, C. (2006) Resilience: the emergence of a perspective for social-ecological systems analysis. *Global Environmental Change* 16, 253–267. doi:10.1016/j.gloenvcha.2006.04.002

Geist, H.J. and Lambin, E.F. (2004) Dynamic causal patterns of desertification. *BioScience* 54, 817–829.

GIAHS (2013) Globally Important Agricultural Heritage Systems, Available at: http://www.giahs.org (accessed February 2013).

Hamilton, A.J., Stagnitti, F., Xiong, X., Kreidl, S.L., Benke, K.K. and Maher, P. (2007) Wastewater irrigation: the state of play. *Vadose Zone Journal* 6, 823–840.

Herrero, M., Thornton, P.K., Gerber, P. and Reid, R.S. (2009) Livestock, livelihoods and the environment: understanding the trade-offs. *Current Opinion in Environmental Sustainability* 1, 111–120. doi:10.1016/j.cosust.2009.10.003

Herrmann, S.M., Anyamba, A. and Tucker, C.J. (2005) Recent trends in vegetation dynamics in the African Sahel and their relationship to climate. *Global Environmental Change* 15, 394–404. doi:10.1016/j.gloenvcha.2005.08.004

Jiménez, B., Drechsel, P., Koné, D., Bahri, A., Raschid-Sally, L. and Qadir, M. (2010) Wastewater, sludge and excreta use in developing countries: an overview. In: Drechsel, P., Scott, C.A., Raschid-Sally, L., Redwood, M. and Bahri, A. (eds) (2010) *Wastewater Irrigation and Health: Assessing and Mitigating Risk in Low-income Countries*. Earthscan, London, International Water Management Institute (IWMI), Colombo and International Development Research Centre (IDRC), Ottawa, pp. 3–27.

Johnston, R. and McCartney, M. (2010) *Inventory of Water Storage Types in the Blue Nile and Volta River Basins*. IWMI Working Paper 140, International Water Management Institute, Colombo. doi: 10.5337/2010.214

Kirkby, J., O'Keefe, P. and Timberlake, L. (1995) *The Earthscan Reader in Sustainable Development*. Earthscan, London.

Knoop, L., Sambalino, F. and Van Steenbergen, F. (2012) *Securing Water and Land in the Tana Basin: A Resource Book for Water Managers and Practitioners*. 3R Water Secretariat, Wageningen, the Netherlands.

Kristjanson, P.M., Thornton, P.K., Kruska, R.L., Reid, R.S., Henninger, N., Williams, T.O., Tarawali, S.A., Niezen, J. and Hiernaux, P. (2004) Mapping livestock systems and changes to 2050: implications for West Africa. In: Williams, T.O., Tarawali, S.A., Hiernaux, P. and Fernández-Rivera, S. (eds) *Sustainable Crop-livestock Production for Improved Livelihoods and Natural Resource Management in West Africa. Proceedings of an International Conference Held at International Institute of Tropical Agriculture (IITA), Ibadan, Nigeria, 19–22 November 2001*. International Livestock Research Institute (ILRI), Nairobi and Technical Centre for Agricultural and Rural Cooperation, ACP-EC (CTA), Wageningen, the Netherlands, pp. 28–44. Available at: http://ilri.org/InfoServ/Webpub/fulldocs/SustainableCropLivestock/Pg028_044%20Kristjanson%20and%20Thornton.pdf (accessed February 2013).

Lybbert, T.J., Aboudrare, A., Chaloud, D., Magnan, N. and Nash M. (2011) Booming markets for Moroccan argan oil appear to benefit some rural households while threatening the endemic argan forest. *Proceedings of the National Academy of Sciences of the United States of America* 108, 13963–13968. doi:10.1073/pnas.1106382108

McCartney, M. and Smakhtin, V. (2010) *Water Storage in an Era of Climate Change: Addressing the Challenge of Increasing Rainfall Variability*. IWMI Blue Paper, International Water Management Institute, Colombo.

Millennium Ecosystem Assessment (2005) *Ecosystems and Human Well-being: Synthesis. A Report of the Millennium Ecosystem Assessment*. World Resources Institute and Island Press, Washington, DC. Available at: www.maweb.org/documents/document.356.aspx.pdf (accessed February 2013).

Morton, J.F. (1987) *Fruits for Warm Climates*. Florida Flair Books, Miami, Florida.

Mugerwa, S. (2009) Effect of reseeding and cattle manure on pasture and livestock water productivity in rangelands of Nakasongola District, Uganda. MSc Thesis, Makerere University, Kampala.

National Research Council (2008) *Lost Crops of Africa: Volume III: Fruits.* National Academies Press, Washington, DC.

Ngigi, S.N. (2003) Rainwater harvesting for improved food security: promising technologies in the Greater Horn of Africa. Greater Horn of Africa Rainwater Partnership and the Kenya Rainwater Association, Nairobi, Kenya.

Olsson, L., Eklundh, L. and Ardö, J. (2005) A recent greening of the Sahel: trends, patterns and potential causes. *Journal of Arid Environments* 63 (3), 556–566. doi:10.1016/j.jaridenv.2005.03.008

Peden, D., Taddesse, G. and Haileslassie, A. (2009) Livestock water productivity: implications for sub-Saharan Africa. *The Rangeland Journal* 31, 187–193. doi:10.1071/RJ09002

Rabia, A.R., Solowey, E. and Leu, S. (2008) Environmental and economic potential of Bedouin dryland agriculture: a case study in the Northern Negev, Israel. *Journal of Management of Environmental Quality* 19, 353–366.

Reij, C., Tappan, G. and Belemvire, A. (2005) Changing land management practices and vegetation on the Central Plateau of Burkina Faso (1968–2002). *Journal of Arid Environments* 63, 642–659. doi:10.1016/j.jaridenv.2005.03.010

Reij, C., Tappan, G. and Smale, M. (2009) *Agroenvironmental Transformation in the Sahel: Another Kind of "Green Revolution"*. IFPRI Discussion Paper 00914, 2020 Vision Initiative. Prepared for the project on Millions Fed: Proven Successes in Agricultural Development, International Food Policy Research Institute (IFPRI), Washington, DC. Available at: www.ifpri.org/sites/default/files/publications/ifpridp00914.pdf (accessed December 2012).

Scheffer, M., Carpenter, S.R., Foley, J.A., Folke, C. and Walker, B. (2001) Catastrophic shifts in ecosystems. *Nature* 413, 591–596.

Scott, C., Drechsel, P., Raschid-Sally, L., Bahri, A., Mara, D., Redwood, M. and Jiménez, B. (2010) Wastewater irrigation and health: challenges and outlook for mitigating risks in low-income countries. In: Drechsel, P., Scott, C.A., Raschid-Sally, L., Redwood, M. and Bahri, A. (eds) *Wastewater Irrigation and Health: Assessing and Mitigating Risk in Low-income Countries*. Earthscan, London, International Water Management Institute, Colombo and International Development Research Centre, Ottawa, pp. 381–394.

Shmida, A. and Darom, D. (1992) *Handbook of Trees and Bushes of Israel.* Keter Publishing House, Jerusalem [in Hebrew].

Solowey, E. (2003) Appendix four, characteristics associated with weediness. In: Solowey, E. *Small Steps Towards Abundance: Crops for a More Sustainable Agriculture*. Biblio Books Israel, Acco, Israel/Biblio Books International, Miami, Florida.

Solowey, E. (2010) Chapter 7. Arboreal pastures. In: Solowey, E. *Growing Bread on Trees: The Case for Perennial Agriculture*. Biblio Books Israel, Acco, Israel/Biblio Books International, Miami, Florida, pp. 106–123.

Stringham, T.K., Krueger, W.C. and Shaver, P.L. (2003) State and transition modeling: a process based approach. *Journal of Range Management* 56, 106–113.

Thornton, P.K., Kruska, R.L., Henninger, N., Kristjanson, P.M., Reid, R.S., Atieno, F., Odero, A.N. and Ndegwa, T. (2002) *Mapping Poverty and Livestock in the Developing World*. International Livestock Research Institute, Nairobi.

Turner, M.D. (2004) Political ecology and the moral dimensions of "resource conflicts": the case of farmer–herder conflicts in the Sahel. *Political Geography* 23, 863–889.

UNCCD (2010) *United Nations Decade for Deserts and the Fight Against Desertification*. United Nations Convention to Combat Desertification, Bonn, Germany.

Vohland, K. and Boubacar, B. (2009) A review of *in situ* rainwater harvesting (RWH) practices modifying landscape functions in African drylands. *Agriculture, Ecosystems and Environment* 131, 119–127. doi:10.1016/j.agee.2009.01.010

Washington-Allen, R.A., and Salo, L.F. (2007) Meeting review: catastrophic thresholds, perspectives, definitions, and applications. *Bulletin of the Ecological Society of America* 88, 219–225. Available at: http://www.esajournals.org/doi/full/10.1890/0012-9623(2007)88%5B219%3ACTPDAA%5D2.0.CO%3B2.

Washington-Allen, R.A., Ramsey, R.D., West, N.E. and Norton, B.E. (2008) Quantification of the ecological resilience of drylands using digital remote sensing. *Ecology and Society* 13(1): 33. Available at: http://www.ecologyandsociety.org/vol13/iss1/art33/ (accessed February 2013).

Weckenbrock, P., Evans, A.E.V., Qaiser Majeed, M., Ahmad, W., Bashir, N. and Drescher, A. (2011) Fighting for the right to use wastewater: what drives the use of untreated wastewater in a peri-urban village of Faisalabad, Pakistan? *Water International* 36, 522–534.

WHO (2006) *Guidelines for the Safe Use of Wastewater, Excreta and Greywater in Agriculture.* World Health Organization, Geneva, Switzerland.

Wilson, T. (2007). Perceptions, practices, principles and policies in provision of livestock water in Africa. *Agricultural Water Management* 90, 1–12. doi:10.1016/j.agwat.2007.03.003

Winpenny, J., Heinz, I. and Koo-Oshima, S. (2010) *The Wealth of Waste: The Economics of Wastewater Use in Agriculture*. FAO Water Reports 35, Food and Agriculture Organization of the United Nations, Rome.