NRC Research Press

REVIEW

Rainwater harvesting for restoring degraded dry agro-pastoral ecosystems: a conceptual review of opportunities and constraints in a changing climate

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Abstract: Water resources in dry environments are becoming scarcer, especially under the changing climate. In response, rainwater harvesting (RWH) is being reemphasized with calls to revive the practice. Ancient knowledge on RWH — mainly the collection through runoff, storage, and use of rainwater for various purposes — is still relevant, especially for dry environments. However, many old practices and technologies may not be suitable or feasible for the present and future. Little has been done to modernize and (or) develop new practices and technologies based on ancient indigenous knowledge. Modernizing old practices or developing new ones and using them in integrated rangelands restoration packages with enabling policy environment can unlock their potential in many water-scarce regions of the world. This paper reviews the state-of-the-art of micro-catchment rainwater harvesting (MIRWH) in dry environments and discusses the opportunities available and the major obstacles faced in using it to restore degraded agro-pastoral ecosystems and support their sustainability. The review highlights the knowledge behind it, the practices developed over the years, and their relevance to today and the future. The paper indicates areas of modernization that can make it more feasible for the future of the dry environments, especially their role in mitigating and adapting to climate change. Conventional and passive approaches to restoring/rehabilitating degraded dry agro-pastoral ecosystems are either too slow to show an obvious impact or not progressing satisfactorily. One main reason is that, because of land degradation, the majority of rain falling on such ecosystems and needed for revegetation is lost with little benefit being gained. Adopting a more progressive intervention to alter the processes of degradation and move towards new system equilibrium is required. MIRWH can enable a large portion of this otherwise lost rainwater to be stored in the soil, and, if used in an integrated packages including suitable plant species and sound grazing management, it may support meaningful vegetation growth and help system restoration. The *Badia* Benchmark project, implemented by ICARDA in Jordan and Syria, has demonstrated the potential for adoption at large scale in similar environments. This case study illustrates the potential and the constraints of this practice.

Key words: rainwater harvesting, micro-catchments, drylands, degraded ecosystems, *badia* restoration.

Résumé : Les ressources en eau dans les environnements secs deviennent plus rares, particulièrement avec le changement climatique. En réponse, on insiste sur la collecte des eaux de pluie (« RWH ») avec des appels à ramener la pratique. Les connaissances anciennes sur la collecte des eaux de pluie – principalement la collecte par le ruissellement, le stockage, et l'utilisation des eaux de pluie pour divers buts – sont toujours pertinentes, particulièrement pour des environnements secs. Cependant, beaucoup de vieilles pratiques et technologies peuvent ne pas être appropriées ni faisables pour le moment et l'avenir. Peu a été fait pour moderniser ou développer de nouvelles pratiques et technologies fondées sur les anciennes connaissances indigènes. La modernisation des vieilles pratiques ou le développement de nouvelles ainsi que leur utilisation dans des programmes intégrés de réhabilitation de parcours dans un cadre de politiques habilitant peut libérer leur potentiel dans plusieurs régions du monde où l'eau est rare. Cette étude passe en revue l'état des connaissances en matière de la collecte des eaux de pluie par microcaptage (« MIRWH ») dans des environnements secs et traite des possibilités existantes et des obstacles majeurs à son utilisation dans la réhabilitation des écosystèmes agro-pastoraux dégradés et le soutien à leur durabilité. La revue fait ressortir les connaissances à l'origine de la MIRWH, les pratiques développées au fil des ans et leur pertinence aujourd'hui et à l'avenir. Cette étude indique les domaines de modernisation qui peuvent la rendre possible pour l'avenir des environnements secs, particulièrement le rôle de ces pratiques dans l'atténuation et l'adaptation au changement climatique. Les approches traditionnelles et passives pour réhabiliter des écosystèmes secs agro-pastoraux dégradés sont soit trop lentes à montrer un impact évident ou ne progressent pas d'une manière satisfaisante. Une raison principale est qu'à cause de la dégradation des terres, la majorité de la pluie tombant sur de tels écosystèmes et nécessaire à la végétalisation est perdue alors que pas grand avantage n'en est tiré. Adopter une intervention plus progressive pour changer les processus de dégradation et aller vers un nouvel équilibre du système est requis. La MIRWH peut permettre de stocker dans le sol une grande partie de l'eau de pluie qui autrement aurait été perdue et, si elle est utilisée dans un programme intégré comprenant des espèces végétales appropriées et une bonne gestion du pâturage, elle peut soutenir une croissance végétale significative et aider à la réhabilitation du système. Le projet « *Badia* Benchmark », mis en œuvre par ICARDA en Jordanie et en Syrie, a démontré le potentiel d'adaptation à grande échelle dans des environnements similaires. Cette étude de cas illustre les possibilités et les contraintes de cette pratique. [Traduit par la Rédaction]

Mots-clés : collecte des eaux de pluie, microcaptage, terres sèches, écosystèmes dégradés, réhabilitation *badia*.

Received 7 August 2016. Accepted 17 October 2016.

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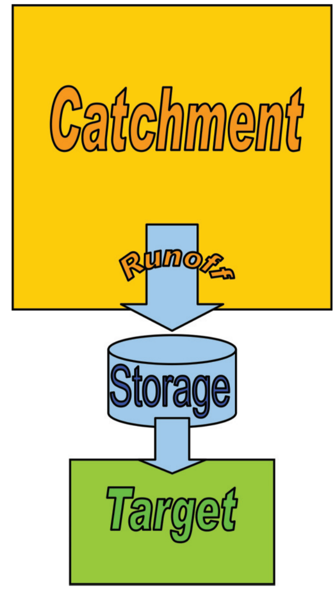
Introduction

Rainwater harvesting (RWH) is defined as *"the process of concentrating rainwater over catchments through runoff to be stored and beneficially used"* (Oweis et al. 2012). It is an ancient practice based on indigenous knowledge that played an important role in building ancient civilizations and in ensuring greater resilience to climate variability, especially is drier environments. Several reviews have addressed the ancient water harvesting systems (Myers and Frasier 1975; Evenari et al. 1982; Boers and Ben-Asher 1982; El Amami 1983; Hudson 1987; Ennabli 1993; Roose 1994; Van Dijk and Reij 1994; Oweis et al. 2004; Julius et al. 2013; Beckers et al. 2013). The ancient systems, some of which had evolved during the Bronze Age or earlier, had provided the main water supply to many ancient settlements in the dry areas of the Mediterranean region and western Asia and some are still in use today. For various reasons, including the huge progress in developing modern water supply technologies, the practice has lost much attention in the last decades (Rango and Havstad 2009). But with increasing water scarcity, especially in drier environments, new calls are being made to revive this practice to contribute to overcome water shortages, enhance resilience of degraded ecosystems, and mitigate/adapt to climate change (Ngigi 2003; Kahinda et al. 2010). Adoption of RWH, in general, is limited even in developed countries, where few policies exist to promote the practice (Schiettecatte et al. 2005; Frican and Grass 2014). However, one must be realistic and not expect miracles from implementing RWH systems. It is true that they have fully supported communities in the past, but these were communities with populations only a fraction of what we have now and with a much lower per capita demand. It was reported by archeologists that in the Middle East, the annual per capita water demand in 1500 AD was estimated at 7 cubic meters, less than 5% of the current water use in Jordan, a water-scarce country. The world population tripled in the 20th century — while water use was multiplied six-fold. "Providing six times more water now than a hundred years ago, an enormous task, has significant impacts on people and the environment" (WWC 2000).

A significant focus still remains on RWH systems that convert rainwater to "blue water" for domestic, industrial, and intensive agricultural purposes. For domestic and industrial use, rooftop RWH has received special attention with emphasis on conveyance and storage facilities (Frasier 1980; Gould and Nissen-Petersen 1999; Falkenmark et al. 2001; Sivanappan 2006; Guo and Baetz 2007; Vohland and Barry 2009; Kahinda et al. 2010; Jones and Hunt 2010; Shadeed and Lange 2010; Andersson et al. 2011; Thomas et al. 2014). This is mainly useful in urban areas, but also rural communities depend on rooftop RWH for domestic use and for irrigation gardens around their houses. RWH for intensive agricultural production is mainly applied in semi-arid, humid, and sub-humid regions, such as those in sub-Saharan Africa, South Asia, and Latin America. (Bruins et al. 1986; Reij et al. 1988; Critchley et al. 1992; Gould and Nissen-Petersen 1999; Rockström et al. 2002; Vohland and Barry 2009; Biazin et al. 2012; Tubeileh et al. 2016). In those environments, the issue is usually drought spells during the rainy season causing soil-water stress and reducing crop yields. Several techniques of RWH are used to benefit from the surplus rainwater during intense storms to collect and store to supplement rainwater during drought spells. RWH for domestic, industrial, and intensive agricultural purposes are not the focus of this review, as several papers have already tackled these topics extensively and may be reviewed in the citations above. Rather, this review will focus on RWH in drier environments that support mainly rangelands agro-ecosystems, such as that exist in the Middle East, North Africa, China, and Northern India.

As vegetation is the main component of dry ecosystems' restoration, one of the main constraints to successful restoration is the lack of sufficient soil moisture for plant growth, in addition to continuing soil erosion, both by water and by wind, which are a cause and a result of degradation (Boers 1994; Oweis et al. 2004). This review addresses that part of the rainwater that is collected and stored in the soil profile and later used directly by plants as "green" water. It is also called "in situ" rainwater harvesting. Further, this review only addresses the role of RWH — its opportunities and constraints — in restoring/rehabilitating degraded dry agro-ecosystems.

Fig. 1. Components of a typical rainwater harvesting system. Source: Oweis et al. 2012. [Colour online.]



Attempts to restore or rehabilitate dryland ecosystems that are mainly agro-pastoral have had little success so far (Dutilly-Diane et al. 2007). The United Nations Convention to Combat Desertification, dryland countries, and relevant organizations have allocated substantial resources to halt or slow down the process of desertification/land degradation in those environments with limited success. Only on a small scale has the restoration of degraded dry ecosystems succeeded (Malagnoux 2009; Nkonya et al. 2016). A case study, presented in this review, of a project planned and managed by the author for Jordan and Syria, illustrates these opportunities and constraints.

Background and context

RWH concept, components, and methods

Water harvesting has been defined in many ways (Myers and Frasier 1975; Critchley and Siegert 1991; Oweis et al. 2012). Authors often mix RWH with other practices or with components/purposes of other systems. To reduce variations, it is necessary to highlight basic RWH system components and processes. There are three biophysical components of all RWH systems (Fig. 1): (*i*) The *catchment* is the area that receives rainfall and processes runoff downstream. It can be either a micro-catchment, with a relatively small area of natural or treated surface (to induce runoff), or a macro-catchment, usually of large surface area, such as natural watersheds with larger amounts of runoff flowing downstream. (*ii*) The *storage* medium, where runoff is stored temporally before being utilized. It can be a pond, a cistern, an aquifer where water is stored for later use, or the soil profile where water is used directly by plants as 'green' water, (*iii*) The *target*, where stored water is being used for domestic, industrial, environmental, and agricultural purposes (Oweis et al. 2012).

The process of RWH involves rainfall runoff — as sheet flow over the catchment area — water storage, and water use for any target purpose. Part of the rainfall leaves the catchment, but part of it stays and may be used or lost to evaporation afterwards. The ratio between water runoff and total rainfall is called the "*runoff coefficient*". So in RWH systems "runoff" occurrence is an essential process, which may be natural or by design. Runoff is essential, especially in low rainfall areas, where for example an annual rainfall of 200 mm cannot support profitable crop or vegetation growth. Runoff allows the concentration of the rain from a larger catchment area into a smaller target area, where the 200 mm falling on the catchment becomes 400 or even 800 mm flowing into the target area, depending on the size of the catchment and the runoff coefficient. Target areas accumulate water runoff from bare catchments upstream, and the biological systems within it operate as though they were in an area of higher rainfall (Rango and Havstad 2009). Tongway and Ludwig 2001, reflected on the impact of concentrating runoff on vegetation and reported that "*in environments with limited rainwater, vegetation productivity is greater if resources are concentrated into patches rather than being distributed uniformly over the landscape*".

Several systems may be wrongly called "RWH systems", as they process no runoff. Examples include the ancient "*qanats*" and some types of soil water conservation practices. Qanats were constructed only to get ground water to the land surface where people could use it for various purposes. There is no runoff involved in such a system. *Qanats* lost importance when modern drilling and pumping equipment were introduced. Some soil water conservation practices, such as some types of terracing, where runoff is actually prevented and rainwater directly infiltrates the soil to be stored in the soil profile for direct use by crops, is another practice that is wrongly called RWH. The contour-bench terraces however, include a catchment strip and processes runoff and are classified under RWH systems. Furthermore, the target of the MIRWH systems need soil water conservation practices to conserve the harvested water and improve its use efficiency (Oweis and Taimeh 2001).

RWH methods and their relevance

RWH methods and systems are classified in several ways, based on one or more of the system components and uses (size of the catchment, means of water conveyance, type of storage, and water use) (Critchley and Siegert 1991; Oweis et al. 2012; Mekdaschi and Liniger 2013). A mixed approach is adopted here to illustrate the systems used.

Micro-catchments, also called in situ water harvesting, have a relatively small surface runoff catchment (from a few square meters to a few thousand square meters), where sheet flow travels short distances (Previati et al. 2010). Runoff water from the catchment is usually applied to an adjacent agricultural area, to be stored in the soil profile to be used directly by plants or in a small reservoir, cistern, or tank, such as rooftop systems, for later use by humans or animals. The catchment surface may be natural or treated with one of the runoff-inducing materials, especially in sandy soils having high infiltration rates (Boers and Ben-Asher 1982; Thomas et al. 2014). Micro-catchments are generally low cost, simple, and convenient as both the catchment and the target are usually within the boundaries of the farmer's property. The catchment, however, occupies a good part of the farm and, to induce runoff, may not be cultivated. Farmers often do not want to give up part of their farms as catchments. Only in low rainfall areas where no crop can be grown without RWH, may farmers be ready to sacrifice part of the land as a catchment. MIRWH includes two major systems (Oweis et al. 2012):

(a) The rooftop systems are usually runoff-induced catchments — house roofs, greenhouse covers, or courtyards paved with materials having very high runoff coefficients. Runoff water is usually stored in tanks, cisterns, jars, or similar devices. Water is used domestically or for livestock watering, but it also can be used inside greenhouses for irrigating cash crops. Water quality issues are of a concern, especially in domestic use. (Ben-Asher et al. 1995).

(b) On-farm systems are usually earthen catchments, but also runoff-induced small catchments are common in some areas, especially in sandy soils serving cash crops. Runoff inducement may be achieved by smoothing or compacting soil surface, by adding impermeable membranes, or treating the surface with paraffin wax or sodium chloride to reduce infiltration (Dutt 1981; Li et al. 2004). Usually, runoff water is stored in the root zone of a target area adjacent to the catchment area and used directly by plants. In some cases, water is collected in ponds and used later for supplemental irrigation of the crops during drought spells (Rees et al. 1991; Oweis and Taimeh 2001). Among the most common on-farm RWH techniques are contour ridges, terraces, bunds, runoff strips, and basins (Oweis and Taimeh 1996; Lasage and Verburg 2015).

Contour ridges and bunds are the focus of the work presented in the case study. These are constructed along the contour lines of sloping land. Contouring is vital in the case of ridges, as any deviation will allow water to flow along the ridge downstream and accumulate at a low point, which may break the ridge and several other ridges below. In some cases, earth ties are installed along the ridge to prevent such flow when the contour is not precise (Critchley et al. 1992; Ali et al. 2010; Oweis et al. 2012).

Spacing between ridges/bunds ranges from 5 to over 20 m and depends on the rainfall amounts and intensity, the slope, soil type, surface roughness (runoff coefficient), and crop water requirements. The ridge/bund is dug to create a small basin leaving the upstream edges clear to allow runoff water to flow into the small basin, infiltrate, and be stored in the soil profile. The height of the ridge/bund should be carefully designed to hold the peak storm runoff volume from the catchment. Traditionally, ridges and bunds are constructed manually. Conventional tillage and sowing machinery such as ridge plough, disk plough, mold board plough, bund former, and disk ridger are also used to form contour ridges and bunds. Although some modifications were made on these implements to adapt to RWH conditions, they did not prove to be adequate for rehabilitating large areas. They proved to be imprecise, tedious, slow and costly. The specially designed implements for RWH purposes are the hydraulically controlled Vallerani "dolfeno" and "Treno", which were adapted to various soils and terrain with subsoiling (Antinori and Vallerani 1994; Malagnoux 2009). The Dolfino was later equipped with contour laser guiding mechanism, which further cut labor cost (Gammoh and Oweis 2011*b*). Seeds and or shrubs and tree seedlings can be grown in the ridges and bund basins. Crops may include field crops, grasses, vegetables, and forages. Runoff in this system brings fertile topsoil from the catchment to the target area together with seeds that find a better environment for emergence and growth (Siegert 1994).

Macro-catchments have a relatively larger surface runoff area, often natural watersheds, but they can also be large artificial catchments (Mzirai and Tumbo 2010). The runoff coefficients of such catchments are usually lower than those of the micro-catchments, as runoff here travels longer with more *opportunity time* for infiltration. Hence there is more opportunity for ground water recharge. Unlike micro-catchments, the catchment area is usually outside the farmer's land, with the farmer having no control over it. Erosion and sediment deposition continue to be problems, especially if the catchment is sparsely vegetated and has cultivation activities.

There are two types of macro-catchment rainwater harvesting (MARWH) (Oweis et al. 2004). (*i*) Long slope systems are prepared outside the *wadis* (Arabic for valleys), mainly along steep slopes for the catchment, and the target is located downstream usually on the flatter slopes. Examples include hillside conduits, *limans*, farm ponds, cisterns, tanks, *hafairs*, and the *tabia*. (*ii*) Flood water harvesting systems use the seasonal water that flows in the *wadis* by either closing the stream bed with small dams to form a reservoir or by diverting water through a conduit to irrigate or store water

Table 1. Criteria used to distinguish between two categories of dryland systems.

Criterion	Dryland system category: Endemic poverty, vulnerable population, pronounced degradation, and extreme environmental variability	Greatest potential to contribute to food security and growth out of poverty
Aridity index	0.3 to 0.35	0.35 to 0.65
Length of growing period	<90 days	90 to 180 days
Environmental risk (as measured by rainfall variability and access to irrigation)	Coefficient of variation >25%	Coefficient of variation ≤25%
Land degradation	High	Low to medium
Market access	Travel time >2 hours	Travel time ≤2 hours

Note: Source: CGIAR Dryland Systems 2013.

off the *wadi* bed. Examples of *wadi*-bed systems include (UNDP/FAO 1987): small reservoirs, *jessour,* and off-*wadi* systems, including water spreading systems, and diversions to ponds and *hafairs* (WOCAT 2012).

Characteristics of the dry ago-pastoral ecosystems

The dry agro-pastoral ecosystems are mainly rangelands occupying the majority of the arid environments of the world. Their aridity index ranges from 0.03 to 0.35 with a growing season length of less than 90 days and an environmental risk coefficient of variation greater than 25%. These systems receive rainfall amounts up to 250 mm in cool winter regions and up to 400 mm in hot summer regions with 50%–100% variability. Although limited in depth, the vast area receives huge volumes of rainwater that are largely lost as evaporation or flow into salt sinks at times when it is desperately needed to support vegetation (Oweis et al. 2012). The CGIAR Dryland Systems (2013) distinguished two categories of dryland (Table 1), those at the wetter side and suitable for intensive agriculture and those at the drier side that are mainly agro-pastoral. The intended systems in this paper are at the drier side of the spectrum, occupy over 30 million km^2 and are host to over 280 million people.

Where surface or groundwater resources are available, intensive agriculture through irrigation is usually practiced in this environment. Some other areas on the drier side are deserts with sand dunes covering most of the land. However, the majority of the area is still rangelands with communities primarily practicing livestock herding and associated activities. Figure 2 shows the target regions classified as arid. Local conditions differ substantially from one place to the other. One common challenge, however, is that those ecosystems are mainly degraded. Reasons include exposure to both human interventions (overgrazing, cultivation, wood cutting, and overuse of water resources) and climate factors (drought and weather extremes), which caused systematic degradation over the years (Evenari et al. 1982).

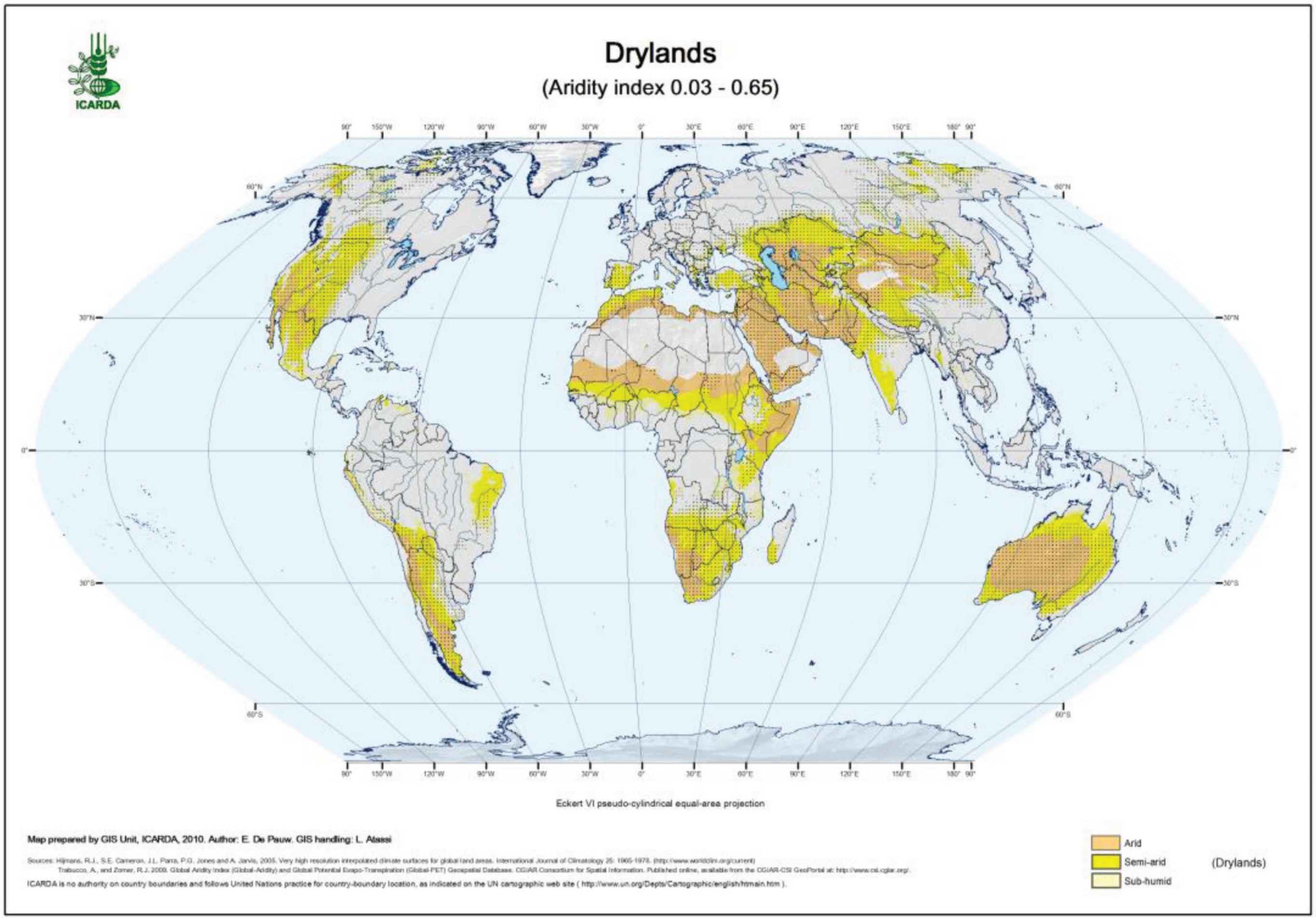
Reports indicate that generally the dry ecosystems were in a better shape not such a long time ago and have sustained local population livelihoods by providing needed ecosystem services, such as animal feed and water resources all year around (Louhaichi and Tastad 2010). Furthermore, it is well established that ecosystem degradation had caused the fall of several ancient civilizations. In the Middle East the "*badia*", the main dry rangeland, provided sustainable ecosystem services for communities' livelihoods only 50 to 100 years ago. Now it is severely degraded with only sufficient sparse vegetation existing after the rainy season to feed animals for one to two months. People and animals migrate to wetter areas for the rest of the year looking for animal feed and water supplies. Similar conditions exist in most of the dry rangelands (Gintzburger and Le Houérou 2005). In Africa, many of the indigenous grasses supported by water harvesting were replaced by crops, such as maize and millet, changing the system's equilibrium and biodiversity (Vohland and Barry 2009). With fragile soil surfaces exposed to the direct impact of rain drops, the process of water erosion continued year after year, taking most of the fertile soils downstream and depriving the rangelands of its productivity. They ended up deposited in dams and salt sinks, further degrading the land. With degraded and cultivated soil exposed to strong winds, erosion by wind causes further loss of surface soil and creates new problems of dust moving to urban areas causing health and transportation problems. The dust originating from the degraded grasslands of Inner Mongolia and the Gobi Desert adversely affects the western parts of Japan and other countries in the region (Wang et al. 2004; Kai and Huiwang 2007). The National Geographic reported on the mega dust storm that hit seven countries of the Middle East in 2015, leaving several people dead, sending thousands of people to hospitals with respiratory problems, and disrupting transportation services, especially at airports (Howard 2015). New socioeconomic realities emerged when communities lost ecosystem services. Many migrated to rural areas, but also new developments were introduced including groundwater exploration and land cultivation, which further aggravated the degradation process.

Restoration of degraded dry ecosystems to their original status may be difficult, if at all possible. Most of the lands in these ecosystems have crossed the so called "threshold of irreversibility". Efforts to rehabilitate them to new ecosystem equilibrium may be a more realistic goal (Aronson et al. 1993). This will require bringing back indigenous components, including the biodiversity (Behnke et al. 1993). There is a consensus, however, that either restoration or rehabilitation would enhance the resilience of the ecosystem and help provide socioeconomic support to the dependent communities (Vohland and Barry 2009).

Attempts to restore degraded dry ecosystems traditionally followed conventional approaches — through protection and some reseeding without major integrated interventions (Holmgren and Scheffer 2001). This approach is a passive one and has achieved limited success because degradation has completely changed the biophysical and socioeconomic processes within these ecosystems. Rainwater that used to infiltrate and be stored in healthy and vegetated lands, supporting sustainable vegetation growth, now runs off, taking fertile soils downstream with it (Oweis et al. 2012). Biodiversity that enhanced the system is no longer there. So, even if protected, the system may not recover to its original status, but take a long time just to show some improvement in vegetative cover. Protection is not an easy task for severely degraded ecosystems, as it has shown limited improvement over long periods (CGIAR 2000). A more progressive approach is to intervene using more intensive approaches. Aronson et al. (1993) indicated that ecosystems that have passed the threshold of irreversibility will require structural interventions combined with revised management techniques for even limited restoration. Those may include land reallocation, reconstruction of seed bank, and alteration of soil physical and chemical properties.

Integrative RWH carries great potential to achieve a meaningful level of restoration in arid environments. This is a progressive integrated approach recommended as an alternative to the conventional passive one. It requires serious interventions to alter the

Fig. 2. The drylands of the world. Source: CGIAR Drylands Systems 2013. [Colour online.]



current process of surface runoff and soil erosion to allow a gradual buildup of soil moisture fertility and seedbank necessary for revegetation (Oweis et al. 2012). RWH is one intervention that has a cost, but the cost of doing nothing to maintain functioning dry agro-ecosystems is much higher than the needed investment to sustain them (Nkonya et al. 2016).

Opportunities with rainwater harvesting

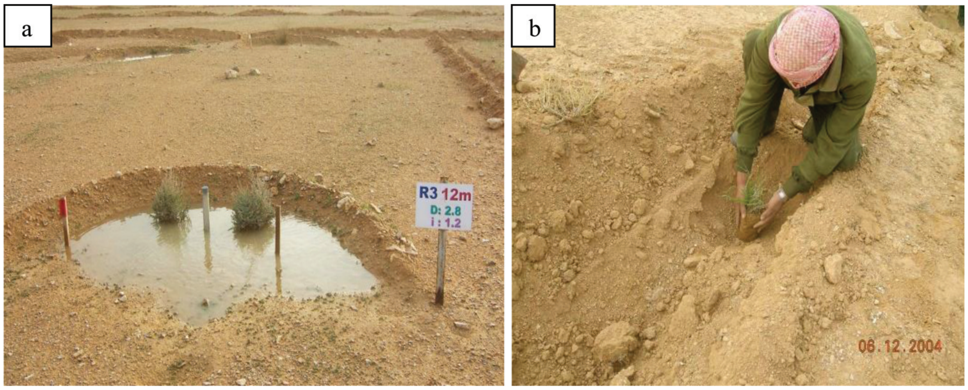
Enhancing soil moisture and vegetation growth

The major portion of the rainfall in this environment runs off the land with limited opportunity and time to infiltrate and be stored in the soil profile. Especially in degraded soils with low infiltration rates, this leaves seeds/plants with little moisture to germinate, emerge, and grow. It also allows more opportunities for soil erosion both by wind and water. MIRWH allows for water to run off a small catchment area into a pit or a ridge and stay there for a long enough time in contact with the soil surface to infiltrate and be stored in the root zone for plant use (Rango and Havstad 2009). The amount of stored water depends on the amount of runoff and the soil storage capacity within the plant root zone (Oweis et al. 2012). Excessive runoff water percolates deeper into the soil and may join the ground water or appear as springs. Previati et al. (2010) conducted thorough field measurements and analysis of the variations in soil water storage between the catchment runoff and the target run-on areas for various ratios and soils in central Tunisia. It was clear that more soil storage was maintained in the run-on profile, and when soil water holding capacity is higher (heavier soils) the benefit of MIRWH in soil-water conservation is clearer. It also showed that excessive runoff water may percolate deeper when the soil water holding capacity is low, such as in sandy or shallow soils. Groundwater recharge is desirable but often is unaccounted for among the advantages of RWH, when it can be used later for domestic and agricultural purposes (Liang and van Dijk 2011).

In degraded soils, especially those with high calcium carbonate content, a crust is formed on the soil surface from the impact of falling rain drops. The crust not only slows down infiltration but also can prevent germinated seed from emerging (Gammoh 2013). This was confirmed by the CGIAR system-wide initiative for conditions in the Syrian *badia*. It was stated that, "Even if shrubs are tolerant to cold environments, establishing them in the dry rangelands is difficult. Surface soil is often crusted and a black moss that spreads rapidly over the soil thwarts emergence." (CGIAR 2000). Engel and Parrotta (2001) confirmed that in afforestation initiatives, much of the reseeding in these soils did not achieve satisfactory results. Research has been conducted to reduce the crust hardening by using chemicals or organic matter, but most of the solutions are either too costly or not sufficiently practical to be applied at larger scales. The MIRWH not only enhances soil moisture, but also prolongs the wetting and softening of the crusted soil surface at the ridges and pits, which helps rangelands seeds to germinate and to emerge (Call and Roundy 1991; Reij et al. 1996).

Soil-water relations change with time at the target areas as a result of implementing MIRWH. Runoff, in addition to seeds, brings organic matter and fertile top soil from the catchment and deposits it at the pits and ridges. In addition, plant growth and rooting systems improve soil water holding capacity and enhance

Fig. 3. (*a*) Manually constructed semicircular bunds planted with salt bush and receiving runoff water after a rainstorm in 2003 in Mhasseh, Syria. (*b*) Manually constructed contour ridge with a farmer planting *Salsola* seedlings in the Jordan *badia* in 2004. Photos by: Theib Oweis. [Colour online.]



soil-water conservation (Hudson 1987). After 8 years of implementing semicircular bunds in the Jordan *badia*, infiltration rate at the bunds increased from 6 mm/h to 11 mm/h, and the soil profile conserved twice the amount of water stored at the catchment area (Karrou et al. 2011).

Controlling soil erosion and combating desertification

It is well established that soil loss by erosion is a major cause of land degradation. Middleton and Thomas (1997) reported that nearly 87% of degraded lands are impacted by wind and water erosion. In arid environments, wind and water erosion is very much influenced by anthropogenic pressures including the overgrazing and cultivation exacerbated by climatic changes, urbanization, and management factors (Ravi et al. 2010). RWH by definition involves runoff, and when the catchment is natural soil, water erosion is inevitable (Boers and Ben-Asher 1982; Oweis et al. 2012). The worst water erosion occurs in large watersheds (catchments) with poor vegetative cover and lack of soil-water conservation measures. Eroded soils are deposited in flat areas, reservoirs, ponds, or lost together with water into salt sinks. However, as said "if you can not prevent it try to control it" and MIRWH practices attempt to control soil erosion within small areas and deposit it in the target areas. Unlike MARWH, runoff travels short distances (usually 2–20 m), gaining only slow eroding velocity before being captured in a ridge or a bond's basin. The amount of soil erosion captured by contour ridges and bunds vary greatly with the spacing, slope, soil type, and cover, and rainfall intensity and amount (Schiettecatte et al. 2005). So MIRWH can largely prevent water erosion from leaving a field or a farm by redistributing it at small target locations. Eroded top soil is usually more fertile and contains higher organic matter. When deposited at the target areas, it improves soil fertility and enhances soil-water conservation processes such as infiltration and water holding capacity (Oweis et al. 2012). Furthermore, eroded topsoil from the catchment includes indigenous plants seeds, which are also deposited at the pits and bunds.

Research in the Jordan *badia* (has shown that the seed rate per square meter in the target ridge/pit is four times that in the adjacent 6–12 m catchment (Shawahneh et al. 2006). The MIRWH process creates an in situ soil- and water-conservation environment at the target areas that is favorable to seed collection with enough moisture for the seeds to germinate and emerge. As soil fertility and moisture are enhanced, chances are greater for the vegetation to overcome drought and for a new habitat/environment to form in these pits and ridges (Fig. 3). Over time the habitat created in the ridges and pits expands naturally and forms a hedge along the contour, occupying a portion of the land that the rainfall/runoff can support (Karrou et al. 2011). Unlike MARWH, erosion by water in MIRWH is controlled in ridges, pits, and bunds and directed to the target area for use by the plants. Other examples where eroded soils are collected and deposited in targets for beneficial use include the common RWH practices of *jessour*, the *tabia,* and the *miskat* in Tunisia (Schiettecatte et al. 2005).

Adaptation to climate change

Climate change may affect all ecosystems, but especially the dry ecosystems as they are more fragile and their resources are limited. These ecosystems are poor in soil organic carbon and have lost a lot by degradation, but they still have the potential to recover and contribute to the mitigation of climate change impacts (Lal 2003; Giorgi and Lionello 2008; Sowers et al. 2011). The potential impacts of climate change on these ecosystems are very complex and vary from one region to the other (Tauer and Humborg 1992; Albalawneh et al. 2015). The main changes that affect dry ecosystem restoration include decreasing annual precipitation, increasing rainfall variability, and higher intensity and frequency of extreme events, such as droughts, rainstorms/floods, and hurricanes (IPCC 2014). Generally, ecosystems will be directly affected by climate change in three ways (HLPE 2015).

1. Increased temperature and CO_2 levels will increase evapotranspiration and reduce soil water (Wreford et al. 2010), which will put more stress on all plants in dry ecosystems, shortening the crop growing periods and reducing yields,
2. Rainfall characteristics are likely to change though predictions lack precision. The Intergovernmental Panel on Climate Change (IPCC) indicates that it is likely that total rainfall in the Mediterranean and subtropics will decrease by up to 20% by the end of the century (IPCC 2014) and,
3. Most important to dry ecosystems are the intensity and distribution of the rainfall. However, methods to estimate trends in precipitation extremes at the local level are still challenging (Willems and Vrac 2011; Willems et al. 2012).

These changes may not be uniform over arid lands because of local topography and other aspects but hold true in general. Assessing the impacts of climate change, not only at the regional but also at the local level, would help better understand how the rainfall patterns are affected by these factors. Methods available for downscaling the outputs of global climate models to local scales have improved substantially, but still need more research (Seguí et al. 2010; Chen et al. 2011; Willems et al. 2012; Lasage and Verburg 2015). Increased intensity will encourage more runoff with higher soil erosion and lower opportunity for infiltration into the soil, especially in degraded drylands. This will cause more moisture stress on plants and reduced recharge of groundwater (HLPE 2015). While this may increase the availability of surface water it may also result in increased floods with associated soil water erosion. Changes in rainfall distribution are likely to intensify drought spells and the duration of droughts, exposing vegetation to increased moisture stress (IPCC 2014). As a result, there will be less support for vegetation and further land degradation. MIRWH can help in adapting to climate change in two ways (Pandey et al. 2003; Oweis et al. 2012; HLPE 2015).

1. More intensive rainstorms will lead to higher runoff rates, especially on degraded lands, with more soil water erosion. As the total rainfall in dry environments will likely be lower, more intense storms imply shorter storm durations, hence less opportunity time for infiltration and storage of water in the soil profile. Here there exists a golden opportunity for adaptation using MIRWH (Kato et al. 2011). Small contour ridges and pits, constructed at short spacing on slopes, will retard runoff acceleration and allow small amounts of runoff water carrying small amounts of eroded soils to be collected and deposited in the basins of the ridges and pits (see previous section on soil erosion). The designs of the spacing between structures and the sizes of the ridges and pits need to be adjusted to account for increased intensities. Furthermore, the reduction of opportunity time for water infiltration, associated with the reduced duration, will be offset by allowing water to stay longer in the pits to infiltrate. In other words, MIRWH increases the opportunity time for infiltration and storage in the soil profile (HLPE 2015). This system has also the potential to enhance groundwater recharge, providing a chance for the conjunctive use of surface and ground water resources to alleviate drought and provide more resilience to the communities in this environment (Liang and van Dijk 2011).
2. It can provide more water storage. Drought is already a challenge in arid environments. Especially in low rainfall areas there could be several years of effectively no runoff (Somme et al. 2004). The communities' response to prolonged drought is to increase storage of water and food. Societal responses included migration, relocation, modification of dwellings, etc. Modifying the dwelling environments by adapting strategies to optimize the use of water, such as RWH, is another alternative (Pandey et al. 2003). However, there is a cost to that and limits to how much storage may be feasible (Guo and Baetz 2007).

The impacts of climate change on domestic water supply and the role of RWH in alleviating it is dealt with in several publications (UNEP 2009; Kahinda et al. 2010). However, for perennial plants, soil moisture storage is usually limited and enough only to support crops for the season. Subsequent droughts leave these plants under extreme stress and dryness with negative consequences for land degradation and communities (Miranda et al. 2011). With climate change, drought is likely to increase and intensify. MIRWH allows adaptation by enhancing soil-water conservation to support plants over more than one season (Previati et al. 2010). This will of course depend on the soil storage capacity and soil-water conservation practices used, but having more water infiltrated and stored gives more chances for shrubs and trees to overcome longer drought spells. In Mhasseh near Palmera, Syria, three years of drought left all vegetation dry except the shrubs planted in semicircular micro-catchment bunds (Somme et al. 2004).

Conjunctive use of water resources

Rainwater can be used directly by plants but can also be stored in surface reservoirs or in groundwater aquifers to be used later (Ali et al. 2007). Usually, blue water supports communities' domestic needs and livestock. In addition to main animal production, communities generally practice limited subsistence farming (gardening) (Biazin et al. 2012). They cultivate drought-tolerant fruit trees, grains, medicinal plants, and vegetables. These are either perennials that need additional water in the dry season, or seasonal that need supplemental water to overcome drought spells towards the end of the wet season. These crops are normally grown in the most fertile and deep soils where more water can be stored in the soil profile. This important function for people is, however, not possible without supplemental water resources (Xiao et al. 2007). Harvesting rainwater in reservoirs/ponds, cisterns, and other containers can provide supplemental irrigation during the dry season and dry spells (Ben Mechlia et al. 2009). Also, it can be used conjunctively with groundwater resources, when available, to provide drinking water for people and livestock (Oweis and Hachum 2006).

The most common and low-cost surface reservoirs are those created by blocking streams with some type of a dam provided with a spillway to pass extra flow downstream. For cost and technical reasons, the size of these reservoirs is usually small. After completely filling the reservoir, there may not be space to store water from subsequent storms and the excess will flow downstream. An opportunity to expand the storage volume may be achieved by moving the first storage in the reservoirs into the nearby soil profile, thus emptying the reservoir to receive new inflows (Oweis and Taimeh 2001). If the soil profile is not full, or additional land is available, further emptying can be made to maximize storage in the season. Water stored in the soil profile supports crops grown through the dry season. Analysis of the likelihoods of storms in the locality is needed to help keep the last storm's stored water for later use. The same strategy can be applied for the enhancement of cistern storage (Ali et al. 2009). One however needs to watch for downstream consequences related to water rights (Bouma et al. 2011). Fortunately, the runoff water in this environment is highly underutilized in most of the regions, and limited conflicts have been reported.

Farmers in this ecosystem grow barley and other animal feed crops with a very high risk of failure. In the Middle East *badia*, only one out of 5 years' sowings of barley produces grains. Still, farmers cultivate crops for various reasons, including establishing land ownership (Mudabber et al. 2011). Failure of the crop further aggravates soil conditions, which contribute to wind erosion. Cultivating feed crops on gentle slopes and in runoff strips can reduce the risk and increase the yields of feed crops. Cultivating the crop on a strip of 0.5 to 1 m wide, leaving an adjacent upstream parallel strip as a runoff catchment 1 to 2 m wide, will allow more runoff water to be stored and used by the crop. Furthermore, the available harvested water in small surface reservoirs can provide one or two doses of irrigation to alleviate drought spells during the growing season (Falkenmark et al. 2001). The opportunities RWH provides for recharge of groundwater and the potential for conjunctive use of resources would substantially enhance water productivity in this ecosystem.

Enhancing water and land productivities

Water productivity is the benefit obtained from a cubic meter of water used or consumed (Molden et al. 2010). Benefits include biophysical, economic, environmental, social, and others. In this dry ecosystem, biophysical and economic water productivity, such as feed, meat, and milk production, and the resulting income from crops and livestock, is important to communities. But also as important are the environmental benefits, including carbon sequestration, biodiversity, erosion and dust control, and wild life enhancement, which are hard to quantify (HLPE 2015). ICARDA indicated that about 90% of the rainfall in the *badia* ecosystem of West Asia and North Africa (WANA) is lost in evaporation or runoff to salt sinks. The rest, about 10%, is beneficially used to support sparse vegetation. RWH enhances water productivity in general by making more rainfall available as transpiration for vegetation (Oweis and Hachum 2006). Oweis et al. (2012) indicated that applying MIRWH and MARWH techniques in the Middle East *badia* may convert about 40% to 50% of the evaporative losses to transpiration by enhancing vegetation cover. Controlling erosion and enhancing soil-water conservation would improve significantly the water and land environmental productivities.

Limits, constraints, and possible measures

Climate uncertainties and storage constraints

Climate variability and change make any development in this ecosystem riskier. As water is the most limiting resource, drought threatens restoration efforts even when RWH is used. In Mehasseh, Syria, *Salsola* and *Atriplex* shrubs planted in semicircular bunds on loamy soils survived up to three consecutive years of drought (Somme et al. 2004). This depends very much on how much runoff the slope can generate and how much of that runoff the soil profile can store. Difficulties in generating runoff can be serious in sandy soils, where the runoff coefficient is very low and where any artificial inducement would be uneconomical and impractical on a large scale. The same applies for storage in light soils with low water holding capacity. Even though one can generate runoff, it will deep percolate beyond the plants' root zones. Prolonged droughts are common in arid climates and the storage provided by RWH is not unlimited. If it is the sole source of moisture for the vegetation, then the investment may be lost after the depletion of the stored water. Most critical here are fruit trees, shrubs, and other perennial crops (Oweis and Taimeh 1996). However, the risk can be reduced for trees by choosing drought-tolerant species, planting these in the deepest and highest water holding capacity soils to sustain the longest drought possible, and by maximizing soil water storage. Also soil-water storage capacity can be enhanced by applying polymers, organic matter, and other water absorption materials. Availability of a supplemental source of water, such as groundwater, would be the optimal solution. Water harvesting reservoirs and cisterns can be used to provide supplemental irrigation water (Ali et al. 2009). As indicated earlier, climate change is likely to intensify droughts, but also provides opportunity for more runoff to be harvested through more extreme events.

Indigenous practices and capacity to modernize

The indigenous ancient knowledge of RWH is still relevant and will continue to be so, but ancient indigenous practices may not be suitable for the present or future climates. People in developing countries are emotionally attached to old practices and continue to use despite them not being practical or cost effective. Modern materials, tools, and technologies are often developed based on the same knowledge, but are more suitable to today's conditions. Using ancient RWH knowledge with modern practices is more relevant (Oweis et al. 2004).

The technical aspects of RWH systems are not simple or easy to implement by unskilled people. Laying ridges on the contour lines, for example, is essential for the proper functioning of the system, but requires training and special skills to do. If not done properly the whole system will collapse, which is a common problem (Reij et al. 1996; Rango and Havstad 2009). Constructing a small farm reservoir across a stream usually needs a spillway to pass the extra flow. Without the spillway the whole structure can collapse, which is also a common problem. Many RWH systems do not function properly because of a flawed design and implementation deficiencies associated with the lack of needed skills. Blame for failure is usually and wrongly directed at the RWH concept (Oweis et al. 2012).

Proper selection of suitable sites for implementing water harvesting systems is not straight forward (Kumar et al. 2008; Kato et al. 2011). RWH systems require specific conditions to function properly. Those may include a specific topography, soil depth and type, surface roughness, vegetation cover, rainfall amounts and intensity, runoff coefficient, crops, etc. Although in most of the situations some type of RWH may be applicable, the failure to match the right method to the site conditions results in an unsuccessful system. Guidelines for the selection at the local level are published for most of the methods (Critchley and Siegert 1991; Oweis et al. 2001; Lancaster 2009; Mekdaschi and Liniger 2013). On a large scale, remote sensing and geographic information system (GIS) tools can be used to classify areas according to their suitability to any type of RWH (Oweis et al. 1998; De Pauw et al. 2008; Ziadat et al. 2012; Mahmoud and Alazba 2015; Albalawneh et al. 2015). Furthermore, GIS-based similarity and suitability analysis can help in out scaling successful applications of specific RWH practices to other areas (Ziadat et al. 2015).

Challenges with integration

Ecosystems restoration is an integrative discipline including applied sciences, landscape architecture, earth sciences, and social sciences. Whether it is structural or functional or a combination of the two approaches, an examination of the degradation dynamics affecting biotic and abiotic components is essential to building a suitable integrative framework for restoration (King and Hobbs 2006; Cooke and Suki 2008). It is well established that failure in projects aimed at restoration of degraded ecosystems and combating land degradation is often due to missing one or more elements of the restoration package. Despite its structural and functional role/impact in altering the degradation process of soil, water, and nutrients, RWH is often ignored in large scale dry ecosystems restoration and rarely integrated in the frameworks for implementation (Rango and Havstad 2009). On the other hand, projects focusing on RWH often ignore other integrative elements of the restoration framework. Implementing RWH practices alone cannot achieve its potential in ecosystem restoration unless it is part of an integrated ecosystem restoration packages (Oweis et al. 2012). Enhancement of soil water requires, to be effective, that appropriate plants species are selected and planted at the right place and time, that soil chemical and biological nutrients are enhanced, that the new vegetative cover is grazed only up to its carrying capacity.

Grazing management in particular is challenging in open grazing areas where herders capture any opportunity to provide feed for their animals (Malagnoux 2009). In the old times in the *badia* of the Arabian Peninsula, the *hima* (indigenous tribal rangelands collective conservation system) prevented overgrazing and ensured equilibrium between the number of sheep, the period of grazing, and the rangelands' feed carrying capacity (Al-Jayyousi 2010). Over the last decades the region has lost the *hima* system with substantial increase in the animals' population, causing further land degradation. The resulted feed shortages had caused governments to subsidize feed supplements, like barley, which in turn encouraged further increase in animal population and further rangeland degradation. Unless this vicious land degradation cycle is broken through proper intervention, new legislations and reformed institutions, the dry ecosystems restoration will have little success (Kilani et al. 2007).

Upstream-downstream consequences

Currently most of the runoff water generated from degraded watersheds in the dry ecosystems flows downstream. However, expanding RWH in the upstream of the watersheds will certainly reduce the flow downstream (Falkenmark et al. 2001; Ngigi 2003; Vohland and Barry 2009; Dile et al. 2016). If this water is already allocated, a conflict can arise over established water rights. It is true that there are few established water rights in these environments, but traditional use of the runoff can also create conflicts. On the northwest coast of Egypt, building small water harvesting reservoirs upstream cut down the normal flow to figs orchards in the coastal areas, where farmers protested against the development. Future conflicts may develop when development expands, although not in the near future as only small portions of the watersheds are developed (Ali et al. 2007).

Where there are no water rights established, the question is where the runoff water is best used across the watershed. As the answer may not always be obvious, a criteria and optimization process is needed to plan such an allocation (Woyessa et al. 2006;

Andersson et al. 2011; Bouma et al. 2011). Maximizing social and environmental benefits may be the objectives, but there could be other objectives at the local level. An integrated watershed management approach, which simultaneously addresses the critical human activities and natural resources issues at the watershed level, can only optimize water harvesting allocation and guarantee an agreed upstream-downstream sharing of the rainwater resources (Oweis et al. 2001; De Pauw et al. 2008; Mahmoud and Alazba 2015).

Lack of enabling environments

Technical solutions to implementing successful RWH initiatives, for domestic water supply and intensive agricultural production, are mostly available and direct benefits are usually favorable for investment (Bouma et al. 2016). However, one of the main obstacles to widespread adoption of RWH in degraded dry rangelands ecosystems is the lack of a favorable environment for investment (UNEP 2009). Like others the rangelands ecosystem services include provisioning, regulating, supporting and those of cultural nature. Except for the provisioning services, which are mainly animal feed, all other benefits in rangelands ecosystem are of an indirect nature. Indirect benefits include reductions in wind erosion and dust with the associated improvement in health benefits, reduced water-induced soil erosion with less sediments being deposited behind dams reducing their capacity, enhanced soil fertility and hence productivity, and other ecosystem services, such as groundwater recharge, carbon sequestration, biodiversity enhancement, and cultural services (Power 2010). Social benefits include reduction of migration to urban areas, employment opportunities in rural areas, and enhancing community structures and spiritual matters. It is now well established that all these are public benefits. Communities in this ecosystem are poor and mainly dependent on direct benefits of rangelands restoration for living. Direct returns to investment, in RWH for rangelands restoration, vary from region and situation to another, but are generally low. Studies estimate however that there are more indirect benefits than direct in this business (Costanza et al. 1997; Liang and van Dijk 2011; Akroush et al. 2014). Dutilly-Diane et al. (2007) reported that in the rangelands of WANA, the environmental benefits (mainly from erosion control and biodiversity enhancement) of a package consisting of controlled grazing, shrub plantation, and water harvesting, range from "large" to "substantial". No quantitative estimates were provided. Would poor communities of this ecosystem be willing to finance non-provisional services on behalf of the whole society/country? This is very much questionable.

Developed countries include provisions for public payments for environmental services, which are incentives for private investment in such ecosystems development. Public payment for non-provisioning ecosystem services do not exist in most of the developing countries as those have a lower priority vis-à-vis poverty alleviation and basic economics (Costanza et al. 1997; Hatibu et al. 2006; Liang and van Dijk 2011; Nkonya et al. 2016).

Rangeland ownership is often public and people and the private sector have little incentive to develop. In many areas, tribal land ownership and various forms of land control exist, but in many cases this can be an obstacle to development. Munamati and Nyagumbo (2010) concluded that land ownership could be a key factor in farmers' ability to scale out RWH. Even when people own the land they find difficulties in attracting the private sector when the direct benefits are not attractive. A business model where the private and the public sectors join in long-term investment may change the status quo, but national policy reforms to create the needed enabling environment including payment for environmental services would be required (Dutilly-Diane et al. 2007; Sample and Liu 2014).

The Middle East *badia* rehabilitation: a case study

The *badia* characteristics

The agro-pastoral system in the eastern Mediterranean (Jordan and Syria), locally called '*badia*', is a typical degraded dry ecosystem. The *badia* forms over 70% of the Jordanian and 60% of the Syrian territories and is home to several million inhabitants who depend mainly on raising sheep and goats. The *badia* receives an annual rainfall of 100 to 250 mm in the cool winter months, mainly between December and March. Of this, about 90% is usually lost to evaporation or quality deterioration in salt sinks. Soils are generally silty with crusty surface and low infiltration rates mainly ranging from 4 to 11 mm/h. This causes a high rate of runoff with coefficients ranging between 21%–36%, reaching 60% in extreme situations of high slopes and intense storms. Summers are hot and dry with temperatures ranging from 20 °C to over 40 °C (Taimeh and Hattar 2006; Haddad 2006; Mudabber et al. 2011).

Because of overgrazing, wood cutting, drought, and the low and sparse rainfall, together with human interventions, vegetation has been degraded and soil erosion by both water and wind has continued for decades. Dust storms and continuous migration to cities had resulted. Now the *badia* can only support one to two months of sheep grazing, with the number of animals exceeding the carrying capacity of the ecosystem (Louhaichi and Tastad 2010).

In 1999, ICARDA with national and international partners started a research program for the rehabilitation of the *badia* in Syria and Jordan based on integrated system restoration (ICARDA 2007). This was followed by another project (Water benchmarks of WANA) that continued the work started earlier and lasted for seven years until 2014. Two representative watersheds were selected for conducting the research and testing the outputs. The watersheds, located in the Mhareb-Majdieh area in the Jordan *badia* and in Mehasseh in the Syrian *badia*, were characterized and equipped for research and out-scaling. The community-based integrated research on the rehabilitation of the *badia* ecosystem was based on integrating MIRWH practices (Karrou et al. 2011).

Package development

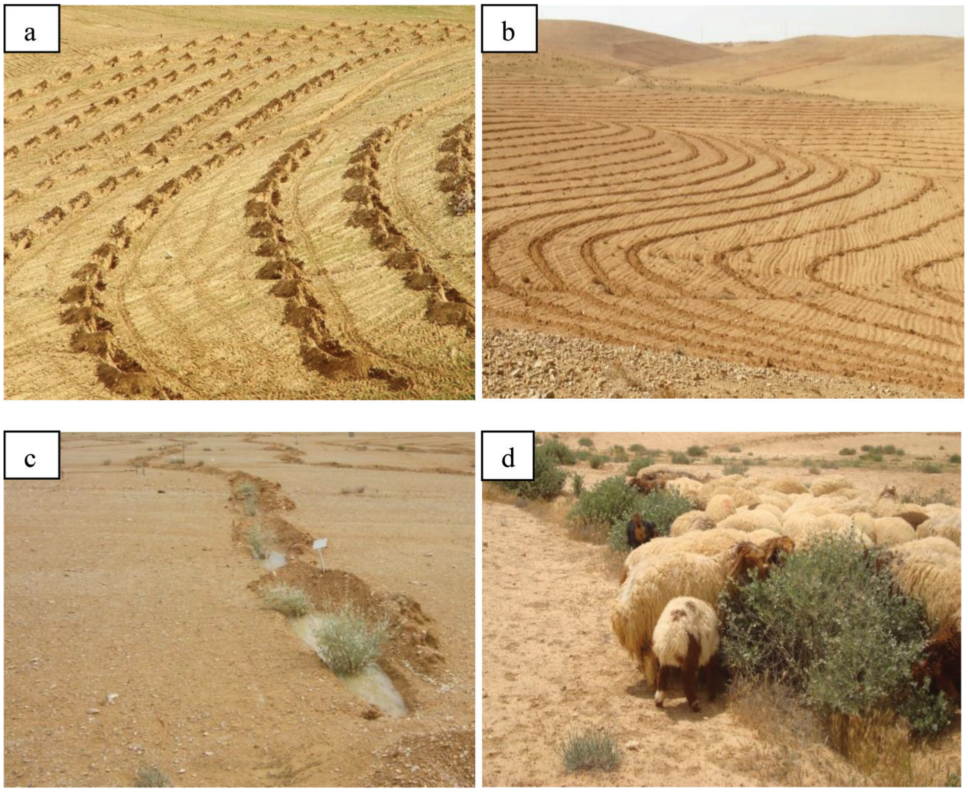
Research on designing, introducing, testing, and out-scaling the integrated RWH package of semicircular bunds and contour ridges were conducted in the two watersheds using *Atriplex halimus* and *Salsola vermeculata* shrubs in three phases.

Phase I. Applied research

This was conducted from 2000 to 2004. Experimental fields were set up in Mhasseh and Mhareb-Majdieh watersheds. Combinations of semicircular bunds and contour ridges with various parameters of size, spacing, and slopes were prepared and planted with *Atriplex halimus* and *Salsola vermeculata*. The structures were constructed manually. Runoff, soil moisture, plant growth, and other parameters were monitored and analyzed annually for four years. The best performing techniques, parameters, and package metrics were concluded for both sites. The package included (Oweis et al. 2006):

1. Constructing contour ridges and semicircular bunds (heights from 30 to 50 cm) at spacing ranging from 6 to12 m, depending mainly on the land slope, with the wider spacing being associated with the flatter slope. The intermittent ridges or bunds 2 to 3 m in length with equal on/off distances were staggered along the rows to better control runoff and soil erosion. Micro catchments areas for a 3 m bund (with equal distance between bunds) and 6 or 12 m spacing are 36 and 72 m², respectively. Annual runoff coefficients at the watershed ranged from 15% to 50%, at slopes from 1% to 20%. Annual rainfall during the experimental period averaged 123 mm with storms intensity ranging from 6–21 mm/h. Runoff coefficients within the plots ranged from 2% to 18%. Various amounts of runoff were col-

Fig. 4. Mechanized MCWH: (*a*) intermittent ridges, (*b*) continuous ridges, (*c*) bunds planted with *Atriplex* and *Salsola* after a rain storm, (*d*) sheep grazing on the vegetation in the restored landscape. Photos by: Theib Oweis. [Colour online.]



lected in the basins after each rainstorm exceeding 10 mm. Bunds received seasonal amounts of runoff water ranging from about 0.4 to 0.8 m^3. Runoff from larger storms occasionally exceeded the basin size and (or) the soil water holding capacity. Soil water storage in the ridges and pits ranged from field capacity, immediately after runoff, dropping to less than 40% of that by the end of the dry season. However on average, the soil moisture content of the bunds and ridges was at least twice that of the catchment. The 6 to 12 m spacing appeared sufficient to provide enough runoff in most seasons (Mudabber et al. 2011).

Fertile top soils that are eroded from the small catchments were deposited, together with indigenous plants seeds, in the bunds and behind the ridges resulting in a more favorable environment for vegetative growth. Total soil erosion from the micro catchments to the bunds/ridges basins ranged from less than 0.5 to 1.4 t/ha annually. About 95% of the runoff and associated soil erosion was kept within the boundaries of the treated field. Seeds and fertile soil eroded from the small catchments were deposited in the bunds and behind the ridges, resulting in a more favorable environment for vegetative growth (Somme et al. 2004; ICARDA 2007).

2. Seedlings of the *Salsola* and *Atriplex halimus* (saltbush) shrubs, not more than one year old, were planted at a rate of 300 to 600 seedlings/ha immediately after the first occurrence of runoff that is sufficient to wet the top soil layer in the basins of the bunds and ridges. Timing was vital to maximize the survival rate of the seedlings and avoid the need for irrigation. Plant yield was monitored over the four years and averaged between 244 and 428 kg/ha for *Salsola* and 668 and 1378 kg/ha for *Atriplex* depending on land slopes and the spacing of the ridges (Karrou et al. 2011; Akroush et al. 2014). After four years, the vegetation covered the bunds and ridges to a width of about 1 m with a rich habitat of various grasses that had germinated and developed under and around the shrubs. Biodiversity enhancement and wildlife were observed to have returned to the landscape (Fig. 4*d*).
3. Grazing management over the research period was done gradually based on development of the shrubs' carrying capacity and to allow the establishment of the vegetation at the bunds and ridges. It was necessary to prevent grazing in the first season and sheep were gradually introduced during the following three years until the shrubs' growth was stabilized. Animal movement over newly constructed bunds caused some damage which required maintenance. However, as the shrubs developed over the years and grasses grew within and on the bunds, the structure was stabilized and no further maintenance was required.

The implementation of this package at the experimental sites in Syria and Jordan has shown that this severely degraded pastoral ecosystem can be revegetated in four to five years by introducing an integrated package of a MIRWH system together with appropriate shrub plantations and sound grazing management. The parameters for the design and implementation under various field conditions were established for this environment (Somme et al. 2004; Karrou et al. 2011).

One of the main limitations to wide dissemination was the cost and time associated with manual planning and implementation of the bunds and contour ridges. On average, three bunds or their equivalent in ridges can be constructed in a man-day. This means that one hectare would require 100 to 200 man-days. In Jordan and Syria this is equivalent to USD1500–3000 per ha. Another USD500 per ha is needed to identify the contour lines, bringing the total cost to around USD2000–3500 per ha. It was concluded that implementing the package using manual labor was slow, tedious, and costly, and often impractical. This was a major obstacle to large-scale adoption, which led to the second phase of the package development — an attempt to mechanize the process (Gammoh and Oweis 2011*a*).

Phase II. Mechanization

The "Vallerani" implement, model Delfino (50 MI/CM), manufactured by Nardi S.p.A., Italy, was tested and adapted to the *badia* of Jordan and Syria. After some modifications it was used to construct the continuous and intermittent ridges/bunds. The testing and adaptation of the mechanized setup was done through a project supported by the Swiss Agency for Development and Cooperation (ICARDA 2007). The machine, as described by Antinori and Vallerani (1994) and Gammoh and Oweis (2011*a*), is a hydraulic single ridge plow with a specially shaped working body, fitted with a sub-soiler, and a programmable hydraulically-operated lifting mechanism. A tractor power take off is used to operate the hydraulic pump. Discontinuous ridges are produced when the lifting mechanism is activated, otherwise the plow can construct only continuous ridges. Four sizes of pit can be obtained with lengths ranging from 1.6 to 4.7 m and with the spacing between successive bunds ranging from 0.7 to 2.3 m.

"The hydraulically controlled movement of the plow bottom while traveling, alternating from an upwards to a downwards motion, simulates the movement of dolphins riding the waves. With each plunge, the plow digs a semicircular micro-basin and forms a pad of earth towards the downhill side for catching runoff" (Gammoh and Oweis 2011*a*). The machine was able to create either intermittent or continuous ridges 1 m wide and 50 cm in height, with a 40 cm ridge depth, plus subsoiling up to 25 cm below the ridge bottom. Subsoiling breaks the hard pans common in the *badia* soils and allows water to infiltrate and be stored deeper in the soil profile (Figs. 4*a* and 3*b*).

The performance of the machine was assessed at typical badia sites of various terrain, slope, and soil conditions. Field tests were carried out at different tractor traveling speeds, pit sizes, and contour spacing. The system performed well in the construction of continuous ridges with lower speed for intermittent ridges. Staggering the bunds at successive contours required special attention (Gammoh and Oweis 2011*a*).

Intermittent bunds have the advantage of being less sensitive to contouring precision, as the bunds are separated by natural ground, but continuous water would flow and destroy the ridges if the continuous contour is not precise. The machine was adapted to the Jordanian *badia* conditions by modifying some parts to overcome topographic and soil-specific conditions and effectively move the soil from the upstream part of the ridge to facilitate runoff flow into the basin. (Karrou et al. 2011).

The plow was tested on a large scale in the Jordan and Syrian *badia,* where one machine was able to construct over 20 hectares per day of intermittent bunds and 30 ha per day of continuous ridges. The cost per hectare was calculated based on the machine constructing 20 ha per day. Considering the capital and operating costs for an assumed 15 year life for the machine operating 240 days/year, the cost per hectare in Jordan was less than USD20. This is a reasonable cost, but the constraint was in fixing the contour lines, which required surveyors to manually identify them in the field. The manual contouring cost per hectare was around USD100–150. This led to the third phase of the development — to automate the contouring process (Gammoh and Oweis 2011*a*).

Phase III. Contour laser guiding

The objective was set to adapt an auto-guiding system to be mounted on the tractor to enable it to follow a contour without demarcation through conventional and costly manual surveying. A low-cost contour laser guidance (CLG) system was selected to suite the contour ridging in the undulating dry rangelands. It was adapted to the site conditions, mounted on the tractor, and tested under actual field conditions (Gammoh and Oweis 2011*b*). The system included a portable laser transmitter and a receiver, connected to a display panel. The system was field-tested in the site where the system capacity was determined under different terrains, slopes, and ridge spacing. The adaptation and implementation of the CLG to the 'Vallerani' unit tripled the system capacity, improved efficiency and precision, and substantially reduced the cost of constructing MIRWH.

The cost per hectare of the laser guidance system assuming a 15 year life for the device is less than USD1.0 per ha (Gammoh and Oweis 2011*b*). The total cost of the restoration package also includes the production, planting, and maintenance of the shrub seedlings — USD11.0 per ha — which brings the total package establishment cost to USD32 per ha. Economic analysis of the investment indicated that planting shrubs with RWH was much more feasible than the traditional way. The economic internal rate of return (EIRR) was estimated at 13% (Akroush et al. 2014). This is confirmed for the same site by Tabieh et al. (2015), but for a range of parameters the authors indicate a range of return from 11.1% to 17.6%. An attempt to quantify the benefits of controlling soil erosion by the package was made by Akroush et al. 2014. The authors used the "opportunity cost approach" of Dung (2001) to evaluate on-site cost of soil erosion as "the loss in the long-term profitability of the farming system from not investing in an economically worthwhile alternative farming system". The contribution of the package in erosion control benefits had raised the EIRR to 17% (Akroush et al. 2014). The relatively high EIRR in this fragile environment is mainly attributed to the large reduction in the implementation cost by full mechanization of the operations. Shrubs productivity was also higher with mechanization as subsoiling provided better infiltration and storage of the runoff water in the soil.

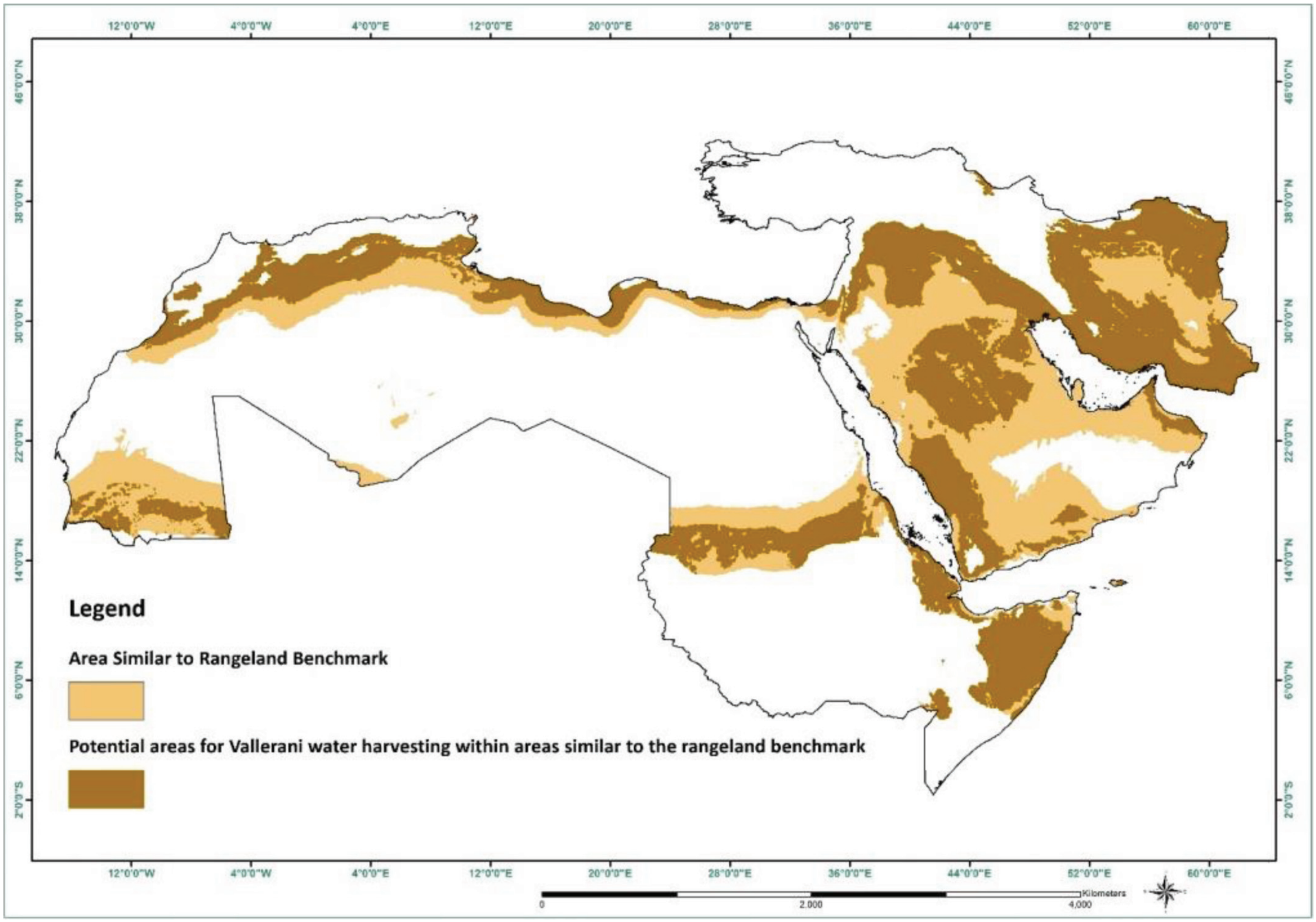
Package testing and dissemination

The package was tested, in collaboration with the National Centre for Agricultural Research and Extension, Jordan, in farmers' fields in the *badia* with full participation of the farmers and the communities. Two communities (Mhareb and Majdieh) located in the testing watershed in Jordan participated in all stages of package development and implementation. As the MIRWH structures were fully mechanized, farmers participated in the preparation, planting, and protection of the shrub seedlings in their fields. The project supported farmers to collect the seeds and produce indigenous shrub seedlings in greenhouses. Later, the farmers managed animal grazing under specialist supervision and protected the fields from trespassing (Karrou et al. 2011).

The package performed well in farmers' fields in that rapid vegetation growth was recorded, soil erosion was largely eliminated at the treated sites, and the environment at the bunds and ridges was enhanced so that the seeds enjoyed better soil moisture and emergence (Shawahneh et al. 2006). A rich habitat was created under the shrubs, which enhanced biodiversity. Generally, the local population was happy with the package and appreciated the benefits of having an additional source of feed for their animals. Adoption studies conducted showed that 80% and 90% of the farmers in the two major communities, Mhareb and Majdieh, respectively, have accepted the package and were willing to adopt it provided that water harvesting structures are supported. The studies also showed that a critical factor for success is regulating grazing access (Akroush and Dhehibi 2015). The legitimate question however, is who should pay for constructing the RWH structures and whether this can be a sustainable business model for restoring this ecosystem?

Mechanization had reduced the establishment cost substantially, in this case to about 32 USD/ha, which is beyond the capacity of the *badia* communities to pay. One additional issue is the large capital investment associated with the machine and associated control mechanisms and capacity to operate. Currently the public sector provides the investments, but ideally the private sector should get involved and costs may even drop further. Con-

Fig. 5. Similarity map of the *badia* rangelands benchmark site of Jordan with a suitability map for the Vallerani water harvesting package in West Asia and North Africa region. Source: Ziadat et al. 2015. [Colour online.]



sidering that the benefits of the restoration are largely environmental, apply for the whole society, and that the farmers in the *badia* are largely poor, it is generally expected that public support is justified. As indicated earlier, payment for environmental services may be one way for governments to support the development. In 2014, the Jordan Ministries of Environment and of Agriculture adopted the package for large-scale rehabilitation of the *badia* and provided needed subsidy for the establishment. Among other interventions, the *Badia* Restoration Program 2014 (Jordan Ministry of Environment 2014) included a component to disseminate the developed package on a large scale and had allocated substantial resources for its implementation. Three machines were allocated and started the implementation in 12 watersheds across the Jordan *badia*. Thousands of hectares have already been developed with plans to continue the program for several years.

Out-scaling through similarity and suitability analysis

Out-scaling the RWH package to other regions required identifying the conditions that are similar to the testing site and the suitability of the terrains for this specific technology. Two types of out scaling maps were developed (Fig. 5) (Ziadat et al. 2015).

- *Badia* benchmark site similarity analysis was undertaken to map areas in all WANA countries that were similar to the *badia* benchmark site in Jordan. Indicators used include climate, soils, and topography. It was found that 6 893 160 km² were similar to the benchmark site environment where the package was developed.
- MIRWH package suitability maps were developed for sites within these similar areas where the developed package could be suitably implemented. The criteria used included slope (from 1% to 25%), soil depth (greater than 50 cm), vegetative cover (less than 25%), and rainfall (more than 100 mm). Those are the special requirements for the Vallerani micro-catchment and other packages. It was found that about 3 240 797 km² of WANA (about 50% of the similar areas) were suitable for applying the package. However, socioeconomic factors such as communities' geographical distribution and their technical and economic capacity for implementation were not considered and should be included in any analysis in the future.

Lessons learned

1. Involvement of the local community from the start of the research and development of the restoration packages is essential for their adoption. Although difficult to control, research processes in farmers' fields are rewarding.
2. RWH alone does not guarantee sustainable restoration of degraded rangelands dry ecosystems. It has to be part of an integrated package including technical, socioeconomic, and management aspects.
3. Managing open grazing in restoration areas is critical but very challenging. It will require new institutional setups to facili-

tate regulated grazing. The principles of the old *hima* system in the Middle East may be useful in this regard.

4. Precision is the key in the selection, design, and implementation of RWH work for its proper functioning. Mechanization helps overcome many of the technical problems associated with unskilled farmers, but generally specialists should be involved in the early stages of the development.
5. It is unlikely that local communities will fully cover the cost of the RWH works and associated activities. As most of the benefits are environmental or social, some sort of public support is essential for any large-scale adoption. Incentives for sound restoration, including subsidies, should be directed to restoration not to supplemental feed. The later encourages increased flocks and further overgrazing.

Conclusions

The large-scale restoration of degraded dry rangeland ecosystems requires more progressive approaches to ensure modification of the biophysical and socioeconomic processes concomitant with land degradation. RWH intervention, if coupled with an integrated technical and socioeconomic package during and after restoration, can be a viable option to support degraded dry rangeland rehabilitation and enhance resilience to climate variability and change.

A major constraint to successful restoration of vegetation cover of degraded dry rangelands is insufficient moisture in the soil profile for plant growth. This is due to the fact that currently most of the rainwater runs off downstream and is lost in salt sinks and evaporation. MIRWH alters the rain runoff process, allowing more opportunity time for the water to infiltrate the soil and be stored for plant use. Furthermore, the practice can control soil erosion by water and provide a better environment for indigenous seeds to collect, germinate, emerge and grow in the target areas.

Grazing management is a huge challenge for dry agro-pastoral ecosystems restoration. Traditional sustainable rangelands management systems are weakened due modern societal evolution. Current policies and institutional setups often result in higher animal population and over grazing. Unless effective community institutions and sound government policies to regulate grazing are in place, effort to reverse or even stop degradation will not be successful.

Sustainability of the MIRWH structures and function over years is critical for successful restoration of the system. As sediments over years gradually fill up the bunds basins, less water collection and storage is achieved. This however, becomes less important as the vegetation cover is restored and functions to slow down runoff and allow for more infiltration and soil water conservation.

Climate change in the dry environments is likely to accelerate land degradation due to intensified drought and increased soil and water erosion. RWH can be an effective response to climate change. It provides opportunity to reduce water velocity, hence control erosion and provide more opportunity time for infiltration, hence enhancing soil water conservation and ground water recharge.

It is vital, however, that public support be ensured through enabling policies, public and private investment, and awareness campaigns, especially in developing countries, to accept and generate support to cover the costs of the environmental and social components of the restoration development.

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