Building resilience against drought: the soil-water management perspective[1]

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Keywords. - Soil-water management; drought; sustainable land management; small-holder farming; rainfed agriculture

Summary. - Many regions in the world are suffering from agricultural drought, i.e., shortage of available water for plant growth. Agricultural drought is not only caused by lack of rain, but is very often associated with an imbalanced partitioning of rainfall. In many drylands, great amounts of water are lost as deep drainage and runoff feeding the blue water resource, i.e., the water in dams, lakes, rivers and aquifers, at the expense of green water, i.e., the soil moisture generated from infiltrated rain that is available for root water uptake by plants. Moreover, a great part of the green water resource is lost as soil evaporation. This imbalanced rainfall partitioning can be improved by adopting a variety of soil-water management practices. This article illustrates how water can be harvested more effectively and crop productivity increased with some examples of recently finished and on-going studies in different overseas continents. However, as soil-water management will surely not solve all water scarcity –related problems, other suggestions for providing more food and fibre per drop hence building resilience against drought will be given.

Trefwoorden. – Bodemwaterbeheer; droogte; duurzaam landbeheer; kleinschalige landbouw; regenafhankelijke landbouw

Samenvatting. - *Droogtebestrijding vanuit het perspectief van bodemwaterbeheer.* - Wereldwijd lijden verschillende regio's aan landbouwkundige droogte, i.e., een tekort aan water beschikbaar voor plantengroei. Landbouwkundige droogte wordt niet enkel veroorzaakt door een tekort aan regen, maar is veelal te wijten aan een onevenwichtige herverdeling van regenval aan het bodemoppervlak. In vele droge gebieden gaan grote hoeveelheden water verloren voor gewassen via diepe drainage en runoff, i.e., blauw water enkel bruikbaar voor landbouw via irrigatie, ten koste van groen water, i.e., het bodemvocht afkomstig van geïnfiltreerde regen dat rechtstreeks beschikbaar is voor wortelopname door planten. Bovendien gaat een groot deel van het groene water verloren onder de vorm van bodemverdamping. Deze onevenwichtige herverdeling van regenval is enerzijds te wijten aan een afnemende fysische bodemkwaliteit (lage infiltratie en waterophoudend vermogen van bodems), vaak t.g.v. bodemdegradatie. Anderzijds gaan aanzienlijke hoeveelheden water voor gewasproductie verloren wegens het ontbreken van gepaste brongerichte en structurele maatregelen. Het beter vastleggen van water in de bodem komt niet enkel landbouwproductie ten goede, maar draagt ook bij tot het leveren van ecosysteemdiensten. In deze publicatie wordt geïllustreerd hoe water effectiever in de bodem kan worden vastgehouden door gebruik te maken van verschillende waterconserveringstechnieken, en in welke mate dit gewasproductiviteit doet toenemen. Omdat bodemwaterbeheer uiteraard niet alle problemen rond watertekort kan oplossen, worden ook andere suggesties om per druppel regen meer voedsel en vezels te produceren en dus bij te dragen tot het opbouwen van meer veerkracht tegen droogte gegeven.

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Mots-clés. - Gestion de l'eau du sol; sécheresse; gestion durable des terres; l'agriculture à petite échelle; l'agriculture pluviale

Résumé. - Résilience contre la sécheresse: la perspective de la gestion de l'eau du sol. - Plusieurs régions dans le monde souffrent de la sécheresse agricole, c'est-à-dire le manque d'eau disponible pour la croissance des cultures. La sécheresse agricole n'est pas seulement le résultat d’un manque de pluies, mais elle est souvent associée à une répartition non-équilibrée de la pluviométrie. Dans plusieurs régions sèches, de grandes quantités d'eau sont perdues par drainage profond ou par écoulement, c'est-à-dire l’eau bleue qui est uniquement utilisable pour l'agriculture grâce à l'irrigation, aux dépens de l'eau verte, c'est-à-dire l'humidité du sol générée par l'eau de pluie qui s'infiltre et qui est disponible pour l'absorption racinaire par les plantes. En outre, une grande partie de la ressource en eau verte est perdue par évaporation du sol. Cette répartition non-équilibrée de la pluviométrie est d'une part due à une détérioration de la qualité physique du sol (faible infiltration et faible capacité de rétention en eau des sols), qui est souvent une conséquence de la dégradation du sol. D'autre part, le manque de structures physiques appropriées pour capter ou collecter l'eau résulte également en ce qu'une grande quantité d'eau soit perdue pour la croissance des plantes. La collecte d'eau ne bénéficie pas qu'à l'agriculture, mais contribue également à produire des services à l'écosystème en général. Cette publication illustrera comment l'eau peut être conservée plus efficacement, utilisant une variété de méthodes de conservation et résultant en une productivité agricole élevée. Cependant, comme la gestion sol-eau ne saura évidemment pas résoudre tous les problèmes liés à la rareté de l'eau, d'autres suggestions pour fournir plus de nourriture et de fibres par goutte de pluie, donc renforcer la résilience à la sécheresse, seront données.

1. Drought and water scarcity

Drought and water scarcity are often in the news. However, there seems to be some misconception about the meaning and causes of drought among the broader public. Conventional meteorological literature (e.g., Keyantash & Dracup 2002) distinguishes between three types of drought: (1) meteorological drought, which refers to shortage of precipitation, (2) hydrological drought, i.e., deficiency in surface and groundwater resources, and (3) agricultural drought resulting from shortage of available water for plant growth. Although the broader public often associates drought with dried out (cracked) soils and crop failure, which typically represent agricultural drought, rainfall anomalies (corresponding to meteorological drought) are generally perceived as its main cause. Moreover, there is a widespread perception that droughts are nowadays occurring more frequently with longer durations of dry spells, and that this is due to global change.

However, there is little scientific evidence that dry spells increase in length and frequency (Stroosnijder 2009). A study in Ethiopia by Seleshi & Camberlin (2006) showed e.g. no significant linear trends with time in duration of dry spells during the *Kiremt* (from June to September) rainy season when analysing daily rainfall data of 11 key stations spread over the country from 1962 to 2002. They even found a decrease in dry spell duration at two stations during the *Belg* (February till May) rainy period. As pointed out by Stroosnijder (2009), similar observations were made in other studies (e.g., Mazzucatro & Niemeijer 2000; Conway et al. 2004; Romero et al. 2007). In a recent study near experimental plots in Sadoré, Niger, we found, using daily rainfall data from 1983 till 2010, no significant changes in length of the growing season, number of rainy days, and duration of dry spells (Wildemeersch et al. 2014).

Rather than that rainfall anomalies, or longer and more frequent dry spells are responsible for more frequent droughts, it is the availability of water for biomass production which is often the bottleneck. In other words, agricultural (or human-induced) droughts and dry spells are occurring more frequently than meteorological ones, as illustrated in Table 1.

Table 1.

Types of water stress and underlying causes in semi-arid and dry subhumid environments (source: Falkenmark & Rockström 2004)

Type of water stress	Drought	Dry spell
Meteorological	Occurrence: 1 out of 10 years Impact: complete crop failure Cause: seasonal rainfall below minimum seasonal plant water requirement	Occurrence: 2 out of 3 years Impact: yield reduction Cause: rainfall deficit of 2-5 week periods during crop growth
Agricultural	Occurrence: >1 out of 10 years Impact: complete crop failure Cause: poor rainfall portioning leads to seasonal soil moisture deficit to produce harvest	Occurrence: >2 out of 3 years Impact: yield reduction or complete crop failure Cause: low plant water availability and poor plant water uptake capacity

The *impact* of global climate change on increased frequencies of droughts and dry spell might therefore be more limited in several regions worldwide than often assumed. According to Wallace (2000), climate change may only marginally affect the annual renewable freshwater resources in some parts of the world with an increase or decrease of these resources of maximum 10%. Moreover, Falkenmark & Rockström(2008) stated that “drylands are in fact not that dry after all”, i.e., there are no hydrological limitations to attain much higher yields than currently attained in smallholder farming. The apparent decline in availability of water for biomass productions is rather due to rainwater partitioning that is becoming poorer. Typically, the amount of available *green water* in the soil is much lower than the available rainfall, due to losses by surface runoff, interception flows and deep percolation (*blue water*), and by soil evaporation (unproductive green water), at least at field scale. On top of that, part of the water present in the rootzone is retained at tensions too high for being available to crops. The poor partitioning of rainwater is illustrated in Fig. 1, which is a synthesis of data from rainfed savanna agro-ecosystems in sub-Saharan Africa (SSA) on controlled research farms (Rockström 2003). Figure 1 shows that in those SSA ecosystems, as little as 15% of rainfall is used productively in plant transpiration. Rockström et al. (1998) reported that on average, in low-yielding smallholder farming systems, yields are in the order of 0.5 ton ha^{-1} and that in such systems, the productive green water flow as crop transpiration can be as low as 5% of rainfall. The poor partitioning of rainwater is very often associated with land degradation and particularly deteriorated physical properties of soil (Stroosnijder 2009) such as reduced infiltrability and water holding capacity, resulting from inappropriate soil management.

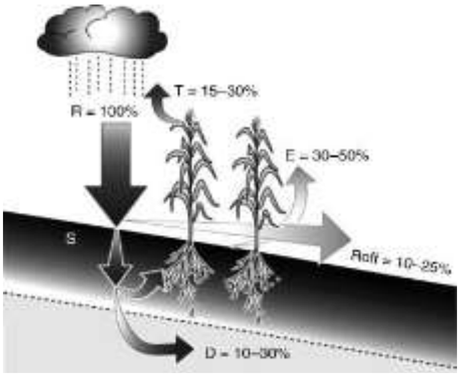

Figure 1.
On-farm partitioning of rainwater R into runoff Roff, drainage or deep percolation D, evaporation E and transpiration T. S refers to rootzone water storage. Interception by leaves is not considered. Values are synthesised data from rainfedsavanna agro-ecosystems in sub-Saharan Africa (SSA) on controlled research farms (Rockström 2003).

It might thus be clear that soils and their management play a central role in the occurrence of droughts (see Fig. 2), as it directly affects the partitioning of rainwater hence affecting the amount of water available for plant growth and thus agricultural drought. Moreover, soil quality does also affect the extent of hydrological droughts, since it determines recharge rates of groundwater. This slowly moving groundwater maintains streamflow and thus assures continuity of surface water resources through base flow, in contrast with storm flow resulting from peak discharge from rapidly flowing runoff water (Dingman 1993). Furthermore, soil quality affects the incidence of meteorological drought through the so called soil-precipitation feedback (Schär et al. 1999). Decreases in evapotranspiration resulting from changes in rainwater partitioning as stated above, do directly or indirectly reduce precipitation locally or over long distances.

However, drought and water scarcity are becoming more alarming with increasing pressures on water resources resulting from the massive increase in the world population with all Millenium Assessment scenarios showing a global population growth till at least 2050 reaching, with medium to high certainty, 8.1–9.6 billion (Millennium Ecosystem Assessment 2005). Parallel with that, per capita income is projected to increase two- to fourfold (Millennium Ecosystem Assessment 2005) which will lead to changing diets, with increased meat consumption, particularly in Sub-Saharan Africa and East Asia (CAWMA 2007). Mekonnen & Hoekstra (2012) estimated that the production of 1 kg of beef requires 15,415 liters of water worldwide, whereas the production of 1 kg of vegetables requires 240 liters and of cereals 1,644 liters. In terms of litres of water needed to produce 1 g or protein, the values are 112, 26 and 21, respectively. Renault & Wallender (2000) calculated that for California the per capita water requirement for an American style diet with high red meat consumption is 5.4 10^3 lit, whereas a vegetarian diet would only require 2.6 10^3liters of water. The real global change our planet is thus facing in terms of pressures to water resources, is the changing population density and increased meat consumption. Producing more food and fibres per drop of water for this growing population with already limited and highly exploited water resources is one of the main challenges in meeting future needs, particularly, in those areas of the world with the highest population growth rates (Wallace 2000).

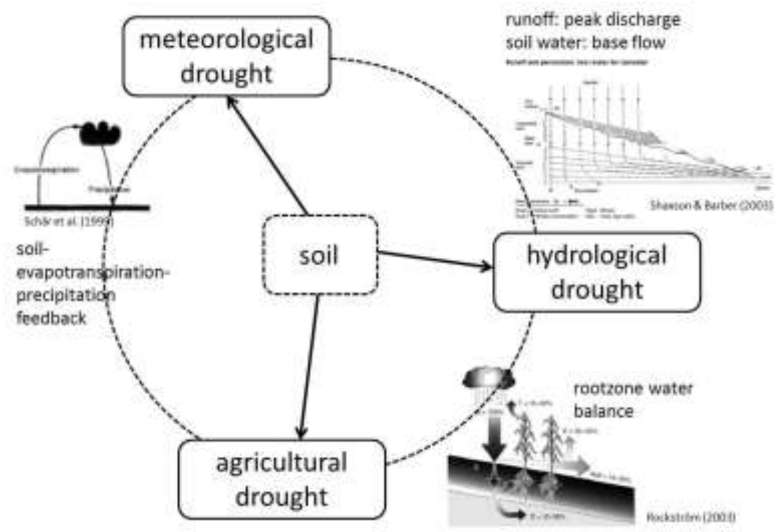

Figure 2.

Soil and their management plays a central role in the occurrence of agricultural, hydrological and meteorological drought

2. Building resilience

Gunderson & Holling (2001) define resilience as the capacity of a system to undergo disturbance and maintain its functions and controls. In the context of this paper, resilience refers in a narrow sense to producing sufficient food and fibre, and thus more food and fibres per drop of rainwater, but at the same time having a system that is capable to adapt, recover, and remain flexible to disturbances in terms of erratic and changing rainfall patterns. In a broader sense it should also concern rendering ecosystem services in general. We particularly believe that soils of good quality are key to a resilient system, as they are the central link between the atmosphere, biosphere, hydrosphere and geosphere. They are the main medium for producing crops and other biomass on land, and for storing, filtering, and transformation of water, nutrients and chemicals (CEC 2006).

Producing more food and fibres per drop of water can be realized through several options. Firstly, given the rather high water demand of producing meat, changing diets towards less meat consumption and thus shifting crop production away from livestock feed (Foley et al. 2011), will result in more food being produced per drop for human consumption.

Secondly, Gustavsson et al. (2011) estimated that one-third of the volume of food is never consumed but is instead discarded, decomposed or used by pests along the supply chain. In developing countries, more than 40% of food is lost post-harvest or during processing due to storage and transport problems. In developed countries, more than 40% of food might be wasted at retail and consumer level. Reducing food waste could substantially contribute to providing more food for human consumption per drop.

A third but minor option could be to expand the area under cultivation. At present, agriculture occupies 38% of the land surface, with 1/3 being crop land and 2/3 pasture. It is estimated that this can increase to maximum 42% in 2050, and this expansion will mainly occur in the tropics where land is most vulnerable to degradation (CAWMA 2007). This means that the impact of this option in producing more food and fibre per drop will only be very limited.

Finally, a fourth and major option for achieving more food and fibre per drop is to improve crop productivity. This includes a broad avenue of practices aiming at increasing crop production per unit of cultivated land and water, such as developing more productive and/or more drought tolerant varieties through (slow) conventional breeding or by using appropriate biotechnological tools, pest control, soil nutrient management, and agricultural water management, among others (Wani et al. 2009). The latter is often associated with irrigation and drainage, and, although there is still room for improvements of irrigation systems through increased irrigation efficiency, use of waste water or expansion of the area under irrigation, it will only to a limited extent contribute to solving the real challenges we are facing. At present, less than 25% of the cropped area is irrigated – with less than 5% in Sub-Saharan Africa (Foley et al. 2011), irrigation often leads to land degradation resulting from salinity and sodicity or puts great pressure on water resources, and capital and knowledge is generally lacking, especially with small-scale farmers, which still represent the majority of crop producers.

In comparison with irrigation and drainage, farmers, research institutes and governmental organisations have given relatively little attention to agricultural water management in rainfed agriculture, because of the general perception that in rainfed systems water takes care of itself (Rockström et al. 2007). However, there is a huge potential for improving crop production in rainfed agriculture that still needs to be unlocked. Because of the very small yields currently achieved under such systems by resource-poor small-holding farmers, substantial gains are to be expected when adopting appropriate rainwater management practices. Rainwater management should be the entry point activity when opting for improved crop productivity. Compared with irrigation, it can be applied on all agricultural lands (Wani et al. 2009). It includes such practices as crop management through e.g. time of seeding, crop selection and plant density, deficit or supplemental irrigation in which crops are only irrigated at critical growth stages with rainwater harvested in reservoirs, and soil management that focuses on *in situ* and *ex situ* harvesting of rainwater. The latter will be elaborated in more detail in section 3.

In order to alleviate the impact of drought by producing more food and fibre per drop, other constraints however such as labour shortage, insecure land ownership, capital constraints and limitation in human capacities (Wani et al. 2009), and socio-economic and market related issues, need to be taken away as well.

Although the previous focused on producing more food and fibres for human consumption, rainwater management practices applied on a larger scale will contribute to a regreening of the landscape, through crops, grasses, shrubs or trees, hence, rendering ecosystem services for society in general (Stroosnijder 2009). A boost in biomass productivity (rise in below/aboveground organic matter) through such practices could also contribute to an increased carbon sequestration and could as such, play a role in mitigating climate change. On the other hand, adopting rainwater management practices is an important adaption strategy to climate change (Kottek et al. 2006). However, the scope of this paper is on building resilience against drought by producing food and fibre for human consumption. This will be illustrated in section 3 with results from some soil-water management projects we have been conducting around the globe in recent years with the focus on *in situ* and *ex situ* harvesting of rainwater. Although the principles of such practices are well known, there is still a great need for research into their effects on rainwater partitioning and crop productivity, so that appropriate and effective measures can be applied in the correct circumstances. Comparison of several studies reported in literature shows that results are not consistent across socio-economic setups, soil types, climate, crops, farm equipment and experiments in different regions in the world. Moreover, most research is empirical. Using computer simulation models as we do in our research (e.g., Verbist et al. 2012) enables better understanding of how rainwater conservation and harvesting practices affect the rootzone water balance and the local hydrology and to improve their design.

3. Soil-water management for increasing plant water availability

One of the most effective options for better managing rainwater is soil-water management (Lal 2008). It encompasses a wide spectrum of practices to improve the partitioning of rainwater hence improving the soil-water balance, and ideally integrate the broad scientific knowledge and expertise of scientists and extensionists with ‘grass-rooted’ local knowledge and farmers’ experience. Such practices range from improving physical soil quality, i.e., primarily increasing rainwater infiltration capacity and plant-available water capacity through the use of soil amendments, conservation agricultural practices and other field water conservation practices, over farming practices such use of mulches and cover crops, to soil conservation practices, and runoff and flood water harvesting techniques. Excellent overviews of soil-water management practices with experiences from a variety of stakeholders worldwide is provided by WOCAT (WOCAT 2007;Liniger 2011). Up-to-date information can be found on their website: www.wocat.net. Table 2 gives an overview of soil-water management strategies and their purpose, and corresponding management options and types for increasing plant-available water to improve crop productivity.

The majority of these practices focus on harvesting of rainwater in its broadest sense. *In situ* or within-field water harvesting has traditionally been termed soil and water conservation practices. However, soil conservation practices were primarily aiming at reducing soil erosion where runoff was more seen as an enemy than as a friend (Falkenmark et al. 2001). Though very effective in reducing soil erosion, they often did not result in yield increases hence their low adaption rate by small-scale farmers. In a narrower sense, Critchley & Siegert(1991) defined water harvesting in agriculture as the collection of runoff for its productive use. As such, it is based on the principle of depriving part of the land of its share of rainwater (which is usually small and non-productive) and adding it to the share of another part in order to meet the water requirements of a given crop (Oweis & Hachum 2006). The narrowest, but commercially most-widely adopted approach to water harvesting is collection of water from roofs or from specially prepared areas of soil (Krishna 2005).

Table 2.

Soil-water management strategies, their purpose and corresponding management options and types for increasing plant-available water to improve crop productivity

Soil-water management strategy	Purpose	Management options	Management type[3]
In-situ water harvesting systems	Maximize infiltration capacity of the soil	Improve topsoil conditions	– Protective surface cover: cover crops, residue, mulches against disruptive action of raindrops – No or reduced soil disturbance by tillage – Conservation agriculture – Soil amendments – Fallowing under cover crops or natural vegetation – Temporary closure of grazing land and subsequent protection
		Improve subsoil conditions	– Deep tillage: subsoiler or paraplough to break-up water restricting layers
	Slow down and/or impede runoff	Increase surface roughness	– Surface cover: cover crops, residue, mulches, geotextiles – Conservation agriculture
		Apply physical structures across slope or along contour	– Terracing: level terraces, bench terraces, Zingg terraces (conservation bench terrace), *fanyajuu* (Swahili, uphill ridge), *fanyachini*(Swahili, downhill ridge), *murundum*(Portuguese, large earth bank), contour bund, graded channel terrace, orchard terrace, platforms, hillside ditches, … – Broad bed and furrow system – Contour field operations – Contour ridges and tied ridges – Impermeable and permeable contour barriers: stone bunds, walls, earth banks, trash lines, live barriers
	Harvest rainwater where it falls	Harvest runoff water	Microcatchments: contour bunds, teras, interrow harvesting, contour bench terraces, triangular and semi-circular bunds (half moon, demi lune), eyebrow, hillslope catchments, Vallerani (micro basins), *zaï* and *tassa* pits (local West-African language, holes), *meskat*(Arabic, rectangular small catchment and cultivated area basin),*negarim*(Hebrew, diamond-shaped small runoff basin) – Macrocatchments: stone bunds, large trapezoidal and semi-circular bunds, hillside conduit

[3]This table lists most widely-used management types. However, the list is not complete and several other local practices (under different names) might exist.

	Optimize available water capacity and drainage beyond the rooting zone	Maximize water retention properties within rooting zone	– Soil amendments – Increase of organic matter pool – Conservation agriculture
		Maximize rooting depth	– Fertilizer/manure to speed up root development – Deep rooting crops – Break-up root restricting layers: chemical, biological/agronomical, mechanical, soil-hydrological solutions
		Optimize drainage beyond rooting zone	– Dry (early) planting – Recharge wells
Ex-situ water harvesting systems	Harvest and divert rainwater	Harvest floodwater	– Floodwater harvesting within stream bed: *jessr*(Arabic, check dam in seasonal stream), *liman*(Hebrew, check dam) – Floodwater diversion: cascade systems
		Harvest groundwater	– *Qanat*(Persian, gently sloping underground tunnel with vertical shafts)
		Store harvested water	– Above ground: rooftop water harvesting in jars and tanks, storage pond, *lac Collinaire* (French, small artificial lakes) – Below ground: cistern
Evapotranspiration management	Minimize water losses from evaporation and excessive transpiration	Minimize soil evaporation	– Surface cover: residue, mulches – Conservation agriculture – Dry (early) planting – Seed priming – Fertilizer/manure to speedup shading – Adjust plant density and response farming
		Minimize unproductive plant transpiration	– Weed control – Crop rotations – Conservation agriculture – Water efficient crops (C_4vs C_3)
		Minimize excessive evapotranspiration	– Windbreaks and shelterbelts – Agroforestry and intercropping – Shading materials

One effective option for harvesting rainwater *in situ* is to *optimize the soil's physical quality*, particularly its infiltration capacity and available water capacity. *Soil amendments* have long been recognised for that purpose. It should be noted that the term soil amendment and soil conditioner are used interchangeably in literature and no clear-cut difference between the two terms are obvious. Whereas soil amendment may be used for materials used to improve all types of soil quality, soil conditioner is generally used for materials to improve soil physical quality. As most substances that are used to improve the soil's physical quality also affect its chemical and biological quality, we use here the term soil amendment. Over the last years we have tested a variety of soil amendments, most of them being waste products of local industries or materials being readily available. We found e.g. on loamy sand in Tunisia that mixing the topsoil with 200 m^3 $ha^{-1}$of a waste fluid by-product of olive mill extraction, locally called *margines*, increased the infiltration capacity of the soil (Mellouli et al. 1998). This was due to a higher degree of aggregation and to a better stability of the aggregates. As compared to the control (untreated soil) the large inter-aggregate pores remained even after being exposed to raindrop impact. The relatively unstable aggregates of the untreated soil were broken down by impacting raindrops resulting in blocking of the largest inter-aggregate pores which consequently led to a reduction of the infiltration rate. Cumulative evaporation of the soil initially brought at field capacity and subjected to potential evaporation of about 10 mm per day, was after 46 days 28% less as compared to the control. The results were much better as when applying the olive mill effluent as mulch by spraying or compared with straw mulch (Mellouli et al. 1998). Moreover, windtunnel experiments at the International Centre for Eremology of Ghent University showed that the amended soil was 43% less sensitive to wind erosion than the control (Abichou et al. 2008).

When mixing highly permeable sandy soils (Arenosol, according to World Reference Base for Soil Resources, FAO, 2006) in Niger with cattle manure and various doses of termite mound material, we found significantly better water retention characteristics and higher macroporosity as compared to the untreated control (Garba et al. 2011). A greenhouse pot experiment showed that tomato (*Solanum lycopersicum* L.) yield in terms of fresh weight of the fruits was much higher in the treated soils, which could have partly been due to their improved nutrient status as well. Similarly, when amending loamy sand (Haplic Podzol) with three compost types that were incorporated in the soil for nine years, its water retention characteristics were improved (higher macro and matrix porosity) (Arthur et al. 2011) which was also reflected in higher fresh weight of tomato fruits. On a highly permeable Ferralsol in Uganda, Obia (2011) found slight improvements in water retention characteristics of the soil, resulting, together with an improved nutrient status, in higher yields of snap bean (*Phaseolus vulgaris* L.). These examples illustrate that water and nutrients should be treated in an integrated way. There is a substantial interaction between water and nutrients, in that soil water affects the availability of nutrients, and vice versa, the availability of nutrients influences the uptake of soil water (Wallace & Gregory 2002).

Another possibility for *improving the soil's quality* is by introducing *conservation agriculture* based practices. Table 2 shows that conservation agriculture serves many purposes and contributes to increasing the available (green) water in more ways than only by improving the soil's quality. According to FAO(2010), 'CA is a concept for resource-saving agricultural crop production that strives to achieve acceptable profits together with high and sustained production levels while concurrently conserving the environment. Conservation agriculture is characterized by three principles which are linked to each other, namely continuous minimum mechanical soil disturbance, permanent organic soil cover, and diversification of crop species grown in sequence or associations.' Apart from improving soil quality in various ways, crop residue reduces the flow velocity of runoff water increasing the time for water to infiltrate, minimizes soil evaporation and reduces excessive transpiration as it controls weeds. In the drylands of Northern China, we found on a Calcisol (silt loam texture) that conservation tillage practices such as no till and non-inversion tillage systems with more than 30% standing wheat residue substantially increased yields of winter wheat (*Triticum aestivum* L.) grown under monoculture (Jin et al. 2007). The yield increases were highest in the driest year of the five-year study (more than 20%). This was attributed to highest quantities of water harvested during the four-month rainy season in summer during which the fields are conventionally left bare. The increased precipitation storage efficiency was due to higher infiltration capacity of the soil and the standing residue slowing down runoff flow velocity and reducing unproductive soil evaporation. These higher amounts of water were than successfully used in the subsequent winter season attaining higher crop transpiration. Additionally, soil erosion (Jin et al. 2008a) as well as soil organic carbon losses (Jin et al. 2008b, 2009a) and nutrient losses (Jin et al. 2009b) were found to be greatly reduced by the conservation tillage practices.

On Vertisols in the drylands of Tigray, Ethiopia, we modified indigenous conservation practices based on making broad beds with furrows at 1.5 m distance and on narrow beds with furrows at 60 cm distance using the local ard plough (scratch plough), so that they comply with conservation agriculture principles. Compared to the conventional system, yields of wheat (*Triticum* sp.) were up to 60% larger in the conservation agriculture based system under semi-arid conditions with maximum wheat yield of 2.6 ton ha^{-1} (Tesfay et al. 2011). Moreover, when calculating gross margins, which considered all costs and incomes from the different practices, the best technique showed an increase of up to 123% (Tesfay 2012). Under dry subhumid conditions, wheat yields were still 30% higher as compared to the conventional system, and attained a maximum value of 5.2 ton ha^{-1} (Tesfay et al. 2012). With all growing conditions being equal, except that glyphosate was added to the CA-based practices to control weeds rather than by tillage, the higher yields were primarily due to an improved partitioning of rainwater and to an improved nutrient status.

In Malawi, we found that after four years of conservation tillage on Luvisols (sandy clay loam texture) under maize (*Zea mays* L.), soil water retention characteristics and nutrient status were improved (Mloza-Banda et al. 2014).Under the conventional ridge tillage system, soils showed poor permeability (for fine textured agricultural soils), with values very close to those below which crop production can be substantially impaired by inadequate root-zone aeration, reduced trafficability, and increased surface runoff and erosion. On the other hand, those under conservation tillage showed values that are ideal for promoting rapid infiltration and redistribution of needed crop-available water, reduced surface runoff and soil erosion, and rapid drainage of excess soil water (Reynolds et al. 2008).

Available water can also be increased by *harvesting runoff water*, which is particularly effective when seasonal rainfall does not meet the crop-water requirements. The idea is then to deprive part of the land of its share of rainwater and to add it to the share of another part in order to meet the water requirements of a given crop (Oweis & Hachum 2006). In arid Niger, we found that on Plinthosols (shallow lateritic marginal soils, locally called *gangani*) *zaï* pits (small circular pits) and *demi lune* microcatchments resulted in substantial agronomical benefits due to a combined effect of improved soil moisture and nutrient status (Wildemeersch et al. 2014). The control treatment only yields straw when manure is applied, whereas zaï produces yields grains similar to those on the deeper fertile Fluvisols in the area (150-600 kg ha^{-1}) and thereby outperforms treatments with demi-lunes and no-till with scarification. Although biological soil quality (nematode count) increased under runoff harvesting practices, soil physical quality parameters derived from the soil water retention curve and infiltration measurements did not improve significantly, revealing that the significant higher soil moisture levels measured by a neutron probe, rather result from the physical design of the applied techniques than from improved soil physical properties. Future work will therefore not only focus on rootzone water balance modelling, but also on the impact of the treatments on soil chemical properties.

In an afforestation project in arid Chile, we found that microterraces, infiltration trenches and a combination of both increased the survival rate of *Eucalyptus globulus* from 0 to 80%, whereas in a semi-arid region in northern Chile, the increase was from 40% to between 75% and 100% depending on the practice (Verbist 2011). Survival rates of *Pinus radiata* increased in the arid region from 80 to 100%, whereas they were 100% in the semi-arid region, even without water harvesting. However, in terms of tree dry weight, the differences were much more pronounced. Even under the wettest climate (semi-arid) the weight increase was more than 800% in case of the Eucalyptus trees and more than 200% in case of the less sensitive Pinus trees. We found e.g., through computer simulations with a fully coupled physically-based surface/subsurface flow model that infiltration trenches reduced runoff under semi-arid conditions with almost 70% as compared to the control (Verbist et al. 2009; 2012; Fig. 3).

In the arid South of Tunisia, we tested whether the cultivated area of an ancient *jessour* (check dam) floodwater harvesting system could be increased to augment the number of olive trees (*Olea europeae* L.) grown. A *jessour*, which occupies the runoff course (*talweg*), consists of a number of *jessr* (*jessour*is the plural of *jessr)*, which is the hydraulic unit made of three components, i.e., an impluvium or catchment area, a terrace or cultivated area and a dyke (*tabia*). We found that four times more olive trees could be grown compared to the number grown by the local community (Gabriels et al. 2005; Ouessar et al. 2009).

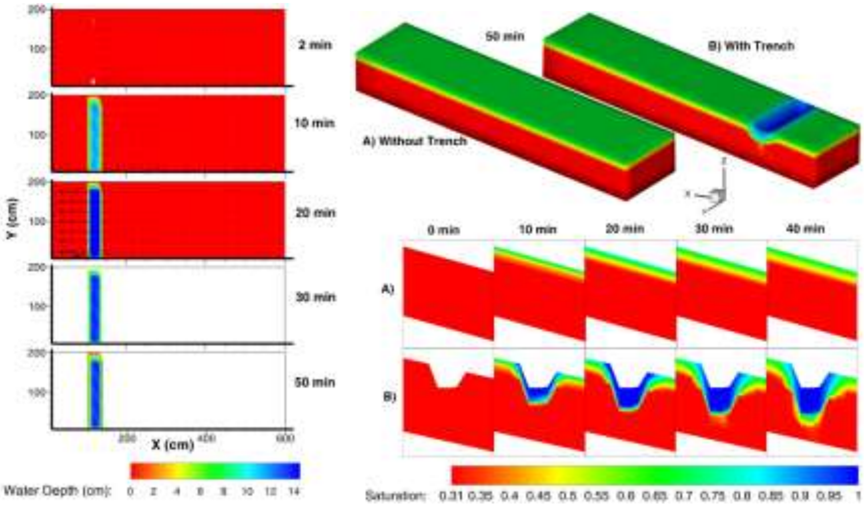

Figure 3.

Left panel: 2D representation of the simulated water depth at the soil surface and in the trench at times 0-50 min. Vectors indicate the overland flow direction and velocity at the node level. Note that the color scale starts at a water depth of $1x10^{-5}$ cm. A white color thus means a zero water depth and no overland flow. Right panel: 3D representation of the simulated soil water content expressed as saturation degree a) without and b) with water harvesting trench at time 50 min. The lower part shows a vertical 2D slice of the soil domain at y=1m and at time 0-40 min (Verbist et al. 2012).

4. Conclusions

Most droughts we are facing are agricultural droughts rather than meteorological ones. This means that plants are more often suffering from lack of available water rather than from a deficit in rainfall. This lack of rainwater is generally due to poor partitioning of rainwater in the soil, with high percentages of water being lost from direct use as runoff or deep drainage (blue water) or as soil evaporation (unproductive green water), at the expense of water used for crop transpiration (productive green water). In order to build resilience against drought hence producing more food and fibre per drop of water, various strategies can be followed. However, better management of rainwater should always be the entry point when opting for improved crop productivity. We have demonstrated that low-cost small-scale soil-water management practices result in small to great increases in crop yield and gross margins. Such practices are hence the way forward for alleviating rural poverty and improving the livelihoods of the rural poor. However, soil-water management alone will not solve all problems. There is a strong need for integrated management with genetic, natural resources and socio-economic components.

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