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Managing water in rainfed agriculture—The need for a paradigm shift

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ABSTRACT

Rainfed agriculture plays and will continue to play a dominant role in providing food and livelihoods for an increasing world population. We describe the world's semi-arid and dry sub-humid savannah and steppe regions as global hotspots, in terms of water related constraints to food production, high prevalence of malnourishment and poverty, and rapidly increasing food demands. We argue that major water investments in agriculture are required. In these regions yield gaps are large, not due to lack of water *per se*, but rather due to inefficient management of water, soils, and crops. An assessment of management options indicates that knowledge exists regarding technologies, management systems, and planning methods. A key strategy is to minimise risk for dry spell induced crop failures, which requires an emphasis on water harvesting systems for supplemental irrigation. Large-scale adoption of water harvesting systems will require a paradigm shift in Integrated Water Resource Management (IWRM), in which rainfall is regarded as the entry point for the governance of freshwater, thus incorporating green water resources (sustaining rainfed agriculture and terrestrial ecosystems) and blue water resources (local runoff). The divide between rainfed and irrigated agriculture needs to be reconsidered in favor of a governance, investment, and management paradigm, which considers all water options in agricultural systems. A new focus is needed on the meso-catchment scale, as opposed to the current focus of IWRM on the basin level and the primary focus of agricultural improvements on the farmer's field. We argue that the catchment scale offers the best opportunities for water investments to build resilience in small-scale agricultural systems and to address trade-offs between water for food and other ecosystem functions and services.

1. Need for investments in water management to upgrade rainfed agriculture

Agriculture plays a key role in economic development (World Bank, 2005) and poverty reduction (Irz and Roe, 2000). In sub-Saharan Africa 35% of GDP comes from the agricultural sector, which also employs about 70% of the population (World Bank, 2000). Growth in the agricultural sector is essential for achieving the Millennium Development Goals (MDGs) of eradicating hunger and poverty. The required growth corresponds to no less than a new green revolution (Conway and Toenniessen, 1999; Falkenmark and Rockström, 2004), with a doubling of food production over the coming 20–30 years, particularly in sub-Saharan Africa and parts of South and East Asia, where malnourishment and growth of food demand are highest (UN Millennium Project, 2005).

No economic sector consumes as much freshwater as agriculture, with an estimated 1300 m^3 cap^{-1} $year^{-1}$ required to produce an adequate diet (Falkenmark and Rockström, 2004). Scenario analysis shows that approximately 7100 km^3 $year^{-1}$ are consumed globally to produce food, of which 5500 km^3 $year^{-1}$ are used in rainfed agriculture and 1600 km^3 $year^{-1}$ in irrigated agriculture (de Fraiture et al., 2007; CA, 2007). The analysis also describes large increases in the amount of water needed to produce food by 2050, ranging from 8500 to 11,000 km^3 $year^{-1}$, depending on assumptions regarding improvements in rainfed and irrigated agricultural systems.

Climate change may further undermine attempts to mobilize the necessary water resources, due to observed reductions in

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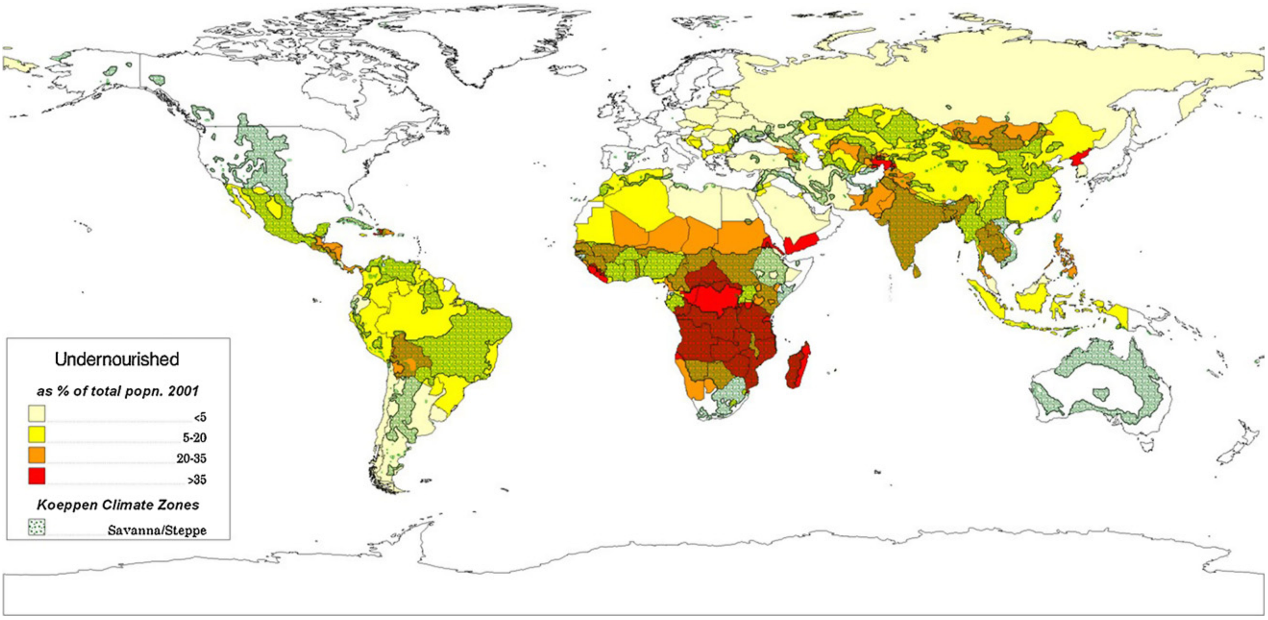

Fig. 1. Number of undernourished as a share of the total population, in relation to the location of semi-arid and dry sub-humid regions (UNStat, 2005).

rainfall in the lower tropical latitudes (Zhang et al., 2007). Some experts are predicting further declines in rainfall and amplification of extreme events (IPCC, 2007). Current irrigation water withdrawals already cause stress in many of the world's major river basins (Molle et al., 2007). The world likely is facing a water crisis with little room for further expansion of large-scale irrigation. This accentuates the need for water management in rainfed agriculture; not only to secure the water required for food production, but also to build resilience for coping with future water related risks and uncertainties. Thus, the current state-of-affairs and future scenarios all point to the same outcome: rainfed agriculture will continue to play a crucial and dominant role in providing food and livelihoods for an increasing world population.

Rainfed crop production, which uses infiltrated rainfall that forms soil moisture in the root zone (the so-called green water resource), accounts for most of the crop water consumption in agriculture. The Comprehensive Assessment of Water Management in Agriculture (CA, 2007) describes a large, untapped potential for upgrading rainfed agriculture and calls for increased water investments in the sector. In this paper we analyze how and where these investments should occur, with the goal of significantly upgrading rainfed agriculture in a sustainable manner.

2. Zooming in on global hotspots

Many farming systems have adapted to hydro-climatic gradients. Examples include pastoral systems in arid environments, agro-pastoral systems in the drier semi-arid zone, and sedentary, multiple cropping systems in the savannah systems and humid agroecosystems. The challenge of upgrading rainfed agriculture through improved water management is concentrated in the world's savannah and steppe regions. These cover the semi-arid and dry sub-humid climate regions where rainfed agriculture is the dominant source of livelihood and where water availability limits crop production (SEI, 2005). Falkenmark (1986) shows a correlation between hydro-climatic constraints and poverty. Countries with a high prevalence of malnutrition and a many poor people depending on farming, commonly are situated in the semi-arid and dry sub-humid (savannah and steppe) climatic regions (CA, 2007) (Fig. 1). We consider these regions to be global hotspots.

3. Large untapped potential—exploiting the yield gap and apparent hydro-climatic constraints

From a global perspective, agricultural productivity is lower in rainfed areas than in irrigated farming systems. In developing countries, rainfed grain yields average 1.5 t ha^{-1}, compared with 3.1 t ha^{-1} in irrigated agriculture (Rosegrant et al., 2002). In temperate commercial agriculture, rainfed yields of major grain crops often exceed 5 t ha^{-1} (FAOSTAT, 2005). Similarly, in tropical regions, yields in commercial rainfed agricultural systems often exceed 5–6 t ha^{-1}. These observations suggest that the apparent biophysical constraints causing low yields in rainfed farming systems in tropical developing countries might be overcome with appropriate management (Rockström and Falkenmark, 2000; Wani et al., 2003a,b).

In Patancheru, India, the yield of a sorghum/pigeonpea intercropping system increased from 1.1 t ha^{-1} with standard practices to 5.1 t ha^{-1} with improved management (Fig. 2). In the dry sub-humid and the semi-arid zones, where farming systems have experienced the lowest yields and the weakest yield improvements during the past decades (FAOSTAT, 2005), dry spell mitigation is a common water management practice for

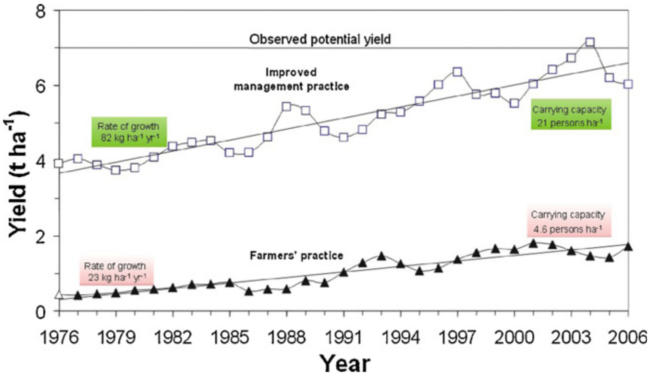

Fig. 2. Long-term crop yields under rainfed conditions. (a) Sorghum grown with farmers' management; and (b) sorghum/pigeonpea grown with improved soil, water, nutrient and crop management. ICRISAT, Patancheru, India.*Source*: Wani et al. (2003a).

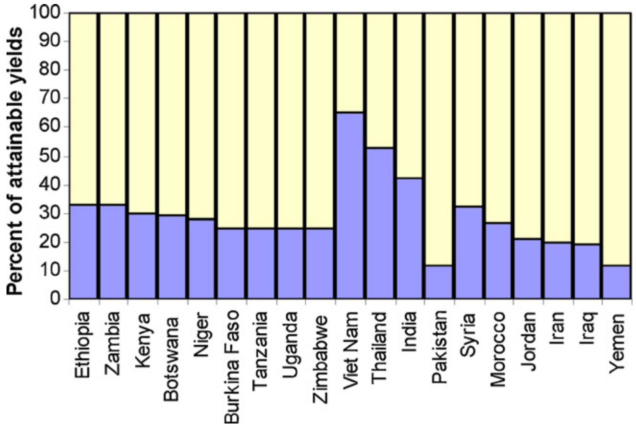

Fig. 3. Yield gaps for major grains in rainfed agriculture, for selected African, Asian and Middle East countries. Actual yields compared to attainable yields.

minimizing the risk of crop failure due to drought. The large gaps between actual and attainable yields in rainfed agriculture in many regions of the world (Fig. 3) suggest a large untapped potential for yield increases.

In the semi-arid and dry sub-humid zone, it is not the *amount* of rainfall that is the limiting factor of production (Fig. 4) (Klaij and Vachaud, 1992; Agarwal, 2000; Hatibu et al., 2003; Wani et al., 2003b). Rather, it is the extreme *variability* of rainfall, with high rainfall intensities, few rain events, and poor spatial and temporal distribution of rainfall. By contrast, in the arid zone, crop water needs often exceed total rainfall, causing absolute water scarcity.

In semi-arid and sub-humid agroecosystems, dry spells (short periods of drought during critical growth stages) occur in almost every rainy season (Table 1) (Barron et al., 2003). By contrast, meteorological droughts occur on average once or twice every decade. Frequencies of both meteorological droughts and dry spells are predicted to increase with climate change (IPCC, 2007). While dry spells can be bridged through investments in appropriate water management techniques, crop yields cannot be sustained during a meteorological drought, and different coping mechanisms are required.

Farming systems often suffer from agricultural droughts and dry spells caused by management induced water scarcity (Rockström et al., 2007). On-farm water balance analysis indicates that in savannah farming systems in sub-Saharan Africa less than 30% of rainfall is used as productive transpiration by crops. On severely degraded land this proportion can be as small as 5% (Rockström, 2003). Thus, crop failures commonly blamed on “drought,” might be prevented in many cases through better farm-level water management.

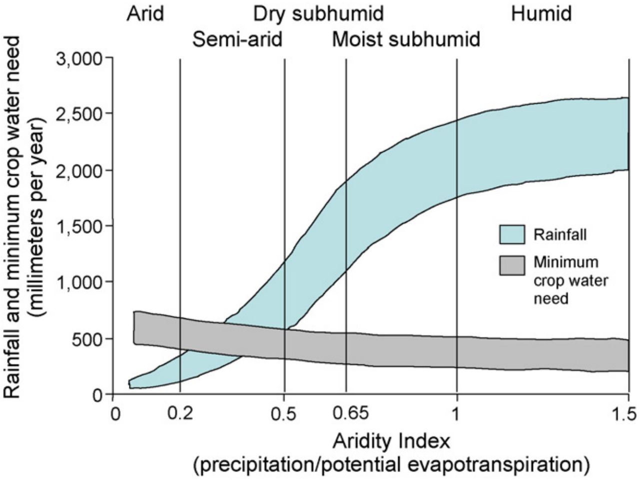

Fig. 4. Range of rainfall variability across hydro-climatic zones from arid to humid agroecosystems. The ecosystem gradient is shown as the aridity index (ratio of annual precipitation to annual potential evapotranspiration). The range in total rainfall is expressed as plus or minus one standard deviation. Minimum crop water needs from Doorenbos and Pruitt (1992) and adjusted for aridity index.

Many non-water factors also limit production in rainfed agriculture. Commonly, nutrient poor soils are the limiting factor to growth (Stoorvogel and Smaling, 1990) even in water scarce regions. Production is also limited by labour shortages, insecure land ownership, inadequate access to capital for investments, and limited skills and abilities. As a result, actual production often falls short of potential output. Rainfed agriculture in regions characterized by erratic rainfall is subject to large inherent water related risks, which make farmers less likely to invest in nutrients and other production enhancing inputs. If these risks can be lowered through investments in water management techniques to bridge dry spells, farmer attitudes regarding agricultural investments might also change. In rainfed areas, rainfall is the most prominent random parameter beyond farmers’ control. Hence rainfall is both a critical input and a primary source of risk and uncertainty regarding production outcomes.

Previous investments in research on dry land agriculture in the savannah zone have shown mixed results in terms of improvements in agricultural productivity (Seckler and Amarasinghe, 2004). This may be due to the lack of focus on water resource management in rainfed areas (CA, 2007). Much of the focus in recent decades has been on erosion control through soil conservation measures, soil fertility, pest control, and crop management. Water has primarily been an issue of *in-situ* moisture management; i.e., maximizing rainfall infiltration through moisture conservation techniques, rather than managing water

Table 1
Types of water stress and underlying causes in semi-arid and dry sub-humid tropical environments.

	Dry spell	Drought
Meteorological		
Frequency	Two out of three years	One out of ten years
Impact	Yield reduction	Complete crop failure
Cause	Rainfall deficit of two- to five-week periods during crop growth	Seasonal rainfall below minimum seasonal plant water requirement
Agricultural		
Frequency	More than two out of three years	One out of ten years
Impact	Yield reduction or complete crop failure	Complete crop failure
Cause	Low plant water availability and poor plant water uptake capacity	Poor rainfall partitioning, leading to seasonal soil moisture deficit for producing harvest (where poor partitioning refers to a high proportion of runoff and non-productive evaporation relative to oil water infiltration at the surface)

Source: Falkenmark and Rockström (2004).

Table 2
Rainwater management strategies and corresponding management options to improve yields and water productivity.

Rainwater management strategy		Purpose	Management options
Increase plant water availability	External water harvesting systems	Mitigate dry spells, protect springs, recharge groundwater, enable off-season irrigation, permit multiple uses of water	Surface microdams, subsurface tanks, farm ponds, percolation dams and tanks, diversion and recharging structures
	In-situ water harvesting systems, soil and water conservation	Concentrate rainfall through runoff to cropped area or other use Maximize rainfall infiltration	Bunds, ridges, broad-beds and furrows, microbasins, runoff strips Terracing, contour cultivation, conservation agriculture, dead furrows, staggered trenches
	Evaporation management	Reduce non-productive evaporation	Dry planting, mulching, conservation agriculture, intercropping, windbreaks, agroforestry, early plant vigor, vegetative bunds
Increase plant water uptake capacity	Integrated soil, crop and water management	Increase proportion of water balance flowing as productive transpiration	Conservation agriculture, dry planting (early), improved crop varieties, optimum crop geometry, soil fertility management, optimum crop rotation, intercropping, pest control, organic matter management

resources to bridge periods of scarcity. A key reason for this mismatch might be the lack of policies governing water management in rainfed agriculture (Hatibu et al., 1999). While water governing institutions traditionally have addressed issues of delivering water to households, industries and irrigation schemes, institutions governing agriculture (e.g., Ministries for Agriculture) have focused on "dry" issues, such as soil management strategies for erosion control. Some researchers and public officials are beginning to focus more closely on water management in rainfed agriculture. Examples include watershed development programmes in India (India, 2005) and agricultural policies implemented in Tanzania (Tanzania Ministry of Agriculture and Food Security, 2003).

4. Potential for new investments in water management techniques

There are two broad strategies for increasing yields in rainfed agriculture when water availability in the root zone constrains crop growth: (1) capturing more water and allowing it to infiltrate into the root zone; and (2) using the available water more efficiently (increasing water productivity) by increasing the plant water uptake capacity and/or reducing non-productive soil evaporation. There is a wide spectrum of integrated land and water management options for use in achieving these aims (Table 2). While most techniques, such as external water harvesting systems, focus on capturing more water, several focus on increasing water productivity directly; e.g., drip-irrigation and mulching. Management approaches aimed at capturing more water often lead also to higher water productivity, as denser crop canopies shadow the soil and thus reduce soil evaporation (Rockström, 2003).

Water harvesting pertains to any practice that collects runoff for productive purposes (Siegert, 1994). A distinction is often made between *in-situ* water harvesting; i.e., the capture of local rainfall on farmland, and *ex-situ* water harvesting; i.e., the capture of rainfall that falls outside the farmland (Oweis and Hachum, 2001).

Supplemental irrigation systems are *ex-situ* water harvesting systems, providing water during periods when rainfall is insufficient to provide essential soil moisture to secure a harvest. In such systems, water scheduling is not designed to meet the full plant water requirements. Instead, the critical importance of the systems is their capacity to bridge dry spells and, consequently, to reduce risks in rainfed agriculture. According to Oweis (1997), supplemental irrigation of 50–200 mm can bridge critical dry spells and stabilize yields in arid to dry sub-humid regions. The potential yield increase in supplemental irrigation varies with rainfall. An example from Syria illustrates that improvements in yields can be more than 400% in arid regions (Oweis, 1997).

Several studies indicate that supplemental irrigation systems are affordable for small-scale farmers (Fan et al., 2000; Fox et al., 2005). However, policy frameworks, institutional structures, and human capacities similar to those for full irrigation infrastructure are required to successfully apply supplemental irrigation in rainfed agriculture.

Rainfed agriculture has traditionally been managed at the field-scale. Supplemental irrigation systems, with storage capacities generally in the range of 100–10,000 m^3, even though small in comparison to irrigation storage, require planning and management at the catchment scale, as capturing local runoff may impact other water users and ecosystems. Legal frameworks and water rights pertaining to the collection of local surface runoff are required, as are human capacities for planning, constructing, and maintaining storage systems for supplemental irrigation. Moreover, farmers must be able to take responsibility for the operation and management of the systems. Supplemental irrigation systems also can be used in small vegetable gardens during dry seasons to produce fully irrigated cash crops. Supplemental irrigation is a key strategy, still underused, for unlocking rainfed yield potential and water productivity.

Soil and water conservation, or *in-situ* water harvesting, has been the focus of most of the investment in water management in rainfed agriculture during the past 50 years. Since *in-situ* water harvesting can be applied on any piece of land and is affordable to most smallholder farmers (e.g., Wani et al., 2003b; Sreedevi et al., 2004), these management systems may already be in place prior to investing in *ex-situ* water harvesting options. Field observations in semi-arid regions of Kenya indicate that the farmers who have adopted or are willing to adopt *ex-situ* water harvesting systems, often also have well advanced practices of *in-situ* water harvesting systems (Mwangi Hai, pers. comm.)[1].

Conservation agriculture[2] is a term describing *in-situ* water harvesting techniques that include a range of non-inversion

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[2] Here conservation agriculture is understood as the equivalent to conservation farming and conservation tillage, i.e., non-inversion tillage systems with mulch. The strict definition of a conservation agriculture system stipulates at least 30% soil cover with mulch throughout the year, which is an important and desirable aim, even though difficult for farmers in savannah regions to attain due to biomass deficiencies.

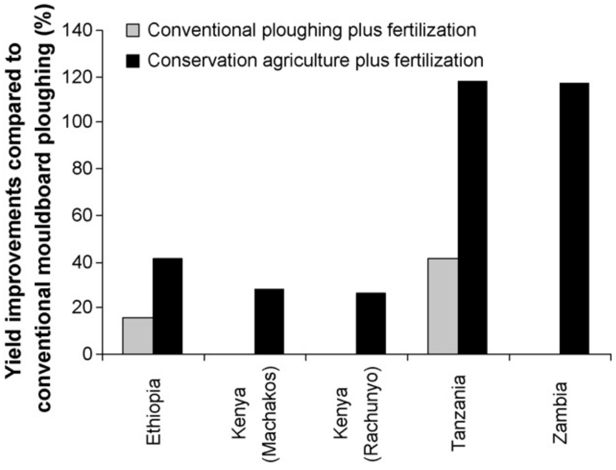


Fig. 5. Maize yield improvements through conservation agriculture in on-farm trials in East Africa.Data from Rockström et al. (2009a).

cultivation systems; i.e., those that involve minimum disturbance of the soil by machines. In most cases, plowing is replaced with a technique such as ripping the soil where seeds will be planted, deep ripping the soil to break up hard or compacted layers (subsoiling), or using direct planting techniques (no-till). Any of these techniques, when used in combination with mulching to build organic matter and improve soil structure, is considered to be conservation agriculture.

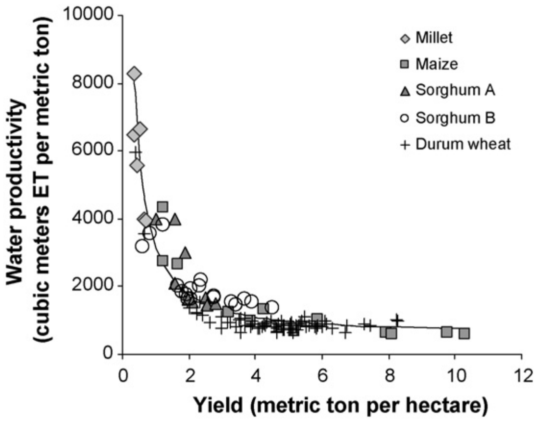
Some form of conservation agriculture is practiced on 40% of rainfed farmland in the United States and has generated an agricultural revolution in several countries in Latin America (Derpsch, 1998, 2005; Landers et al., 2001). Moreover, conservation agriculture is common among small-scale farmers on the Indo-Gangetic plains (Hobbs and Gupta, 2002). Examples from sub-Saharan Africa show that converting from plowing to conservation agriculture results in yield improvements ranging between 20% and 120%, with water productivity improving from 10% to 40% (Fig. 5) (Rockström et al., 2009b). Other advantages of non-inversion tillage systems include a savings in labour related to plowing. Potential disadvantages include higher costs of pest and weed control, the cost of acquiring new management skills, and investments in new planting equipment. Conservation agriculture is relatively cheap to implement, however, and it can be practiced on all soils and does not require water storage devices. As a result, the approach is quite important for upgrading rainfed agriculture, which often is constrained by lack of investment capital.

In semi-arid areas up to 50% of the rainfall is lost from the fields as non-productive soil evaporation (Rockström, 2003). Converting some of that water to productive transpiration through evaporation management will increase water productivity in the arid, semi-arid and dry sub-humid regions. Options to reduce soil evaporation include dry planting, conservation agriculture, and mulching. Higher water productivity is achieved also by improving crop yields. When yields are low (between 1 and 2 t ha^{-1}), even small improvements in yield will generate large gains in water productivity (Fig. 6). This non-linear relationship between water productivity and yield is due to the shading of the soil when the crop canopy becomes denser with higher yield, thus changing the ratio between productive transpiration and non-productive evaporation (Rockström, 2003). Hence efforts to improve crop yields are beneficial from both water saving and income enhancing perspectives.

5. Balancing water for humans and nature

Every increase in water use in agriculture will inevitably affect water availability for other uses, such as drinking water supply and ecosystem enhancement. Upgrading rainfed agriculture may result in water trade-offs with downstream users and ecosystems (Calder, 1999), particularly in closed and closing basins, where more water is used than is renewably available during some portion of the year (Molden et al., 2001; Molle, 2003). In other cases the downstream impacts on stream flow from small-scale water storage systems have been limited, even if implemented widely (Evenari et al., 1971; Schreider et al., 2002; Sreedevi et al., 2006).

Because evaporation management (i.e., shifting non-beneficial soil evaporation to beneficial transpiration) does not directly impact local runoff, this strategy creates a large opportunity for improving yields from rainfed agriculture without affecting downstream water users and ecosystems. By contrast, water harvesting strategies that decrease runoff can have negative impacts downstream. However, capturing runoff close to the source, as is the case for water harvesting systems, may result in lower consumptive water losses by reducing the transmission losses encountered when locally generated surface runoff flows to downstream rivers. However, this theory has not yet been verified. Capturing runoff may also reduce land degradation from water erosion, improve water quality, and retain water at higher altitudes, where it can be used to extend gravity-fed supplemental irrigation (Bewket and Sterk, 2005). In some cases the conversion of natural ecosystems into agriculture has reduced evapotranspiration (Gerten et al., 2005), and forestry has been shown to reduce runoff in South Africa (Jewitt et al., 2004). Expanding the



Source: Millet, Rockström et al., 1998; maize, Stewart 1988; sorghum A, Dancette 1983; sorghum B, Pandey, et al., 2000; durum wheat, Zhang and Oweis 1999; regression line after Rockström 2003.

Fig. 6. Dynamic relationship between green water productivity and yield for cereal crops under various management and climate conditions.*Source*: millet, Rockström et al. (1998); maize, Stewart (1988); sorghum A, Dancette (1983); sorghum B, Pandey et al. (2000); durum wheat, Zhang and Oweis (1999); regression line after Rockström (2003).

area under cultivation might thus increase runoff, depending on the original land use. The downstream impacts of large-scale water harvesting efforts and land use change are highly site specific. Basin-scale hydrological research is needed to enhance understanding of the impacts.

Water plays a critical role in sustaining both aquatic and terrestrial ecosystem services (Falkenmark et al., 2007) and maintaining their resilience to cope with shocks, such as extreme droughts or floods (Folke et al., 2002). Maintaining ecosystem services in an agricultural landscape can be helpful in managing water resources. For example, sustaining a high spatial configuration of different land use types (e.g., forests, grasslands, wetlands, cropland) can conserve green and blue water resources, improve the release rate of blue water, and increase the sources of income. This is particularly relevant for rainfed systems under a changing climate with more frequent shocks. Trends during the past 50 years indicate that expanding agricultural land has been the major cause of degradation of ecosystem services (MA, 2005). Meeting the Millennium Development Goals on hunger might require that agricultural land expands by 0.7% per year (Rockström et al., 2007), putting further pressure on ecosystems.

6. Towards a paradigm shift to water management in rainfed agriculture

Despite the numerous opportunities for upgrading rainfed agriculture through new water management investments to reduce yield gaps and enhance water productivity, efforts in this area have so far largely been lacking. Needed now are new water management policies and investments in human capacities, research, institutional development, and specific technologies.

New policies should be based on an ecohydrological perspective in which rainfall is regarded as the freshwater resource (Falkenmark and Rockström, 2004). However, the focus of Integrated Water Resource Management (IWRM) remains on planning, allocating and managing blue water resources for irrigation, industry, and water supply, while recognizing the need to safeguard environmental water flows for aquatic ecosystem functions in rivers, lakes, wetlands, and estuaries. Yet key ecosystem services, such as agricultural production, depend on green water in terrestrial ecosystems. Hence green and blue water resources should be planned and managed together, forming a new, widened approach to IWRM.

In such a paradigm shift, water harvested at the local scale for crop production will be recognized as a productive water use. Thus, water resource governance and management encompass both the local (catchment) scale, which is relevant to most rainfed agricultural systems, and the larger basin scale, in a nested approach.

One implication of the evidence and arguments in this paper is that a new approach to IWRM should focus more closely on downscaling water resource management from the river basin to the catchment scale (generally below 1000 km^2). An integrated analysis of water resources across scales may illustrate interesting win–win opportunities between upstream green water investments (such as water harvesting) and implications for downstream water uses (such as reduced sedimentation).

In rainfed agriculture, emphasis must be on securing water to bridge dry spells and to increase agricultural and water productivity through new technological water management options, facilitated through institutional and policy interventions. This must be done without decreasing resilience in agricultural landscapes.

A natural consequence of a re-orientation of water resource management, starting from rainfall as the freshwater resource, is to abandon the current (artificial) divide between irrigated and rainfed agriculture. Irrigated agricultural systems generally depend, in part, on contributions from green water. Conversely, the most promising avenue to upgrade rainfed agriculture in regions with water constraints is to invest in blue water management options, such as supplemental irrigation. Breaking this governance divide will be an important strategic step toward raising the institutional priority regarding investments in rainfed agriculture. It will also provide a larger set of management alternatives, ranging from fully rainfed to fully irrigated systems.

Also needed are investments in local institutions, such as farmers' organizations and small-scale credit schemes, which are particularly important in this context, as many farm households cannot afford the initial costs required for small-scale water harvesting (Fox et al., 2005). Public investments in infrastructure such as roads are crucial so that farm produce can be transported easily to markets. Furthermore, private investors must be attracted to investments in rainfed agriculture. Investments are needed also in capacity building, as the lack of knowledge on farms and among extension service personnel regarding water harvesting and conservation agriculture can limit yields in rainfed areas (Rockström et al., 2009a), engendering development initiatives are needed, as women play major roles in agriculture, particularly in rainfed areas. Finally, investments in strategic research are needed to bridge the gap between achievable and potential yields.

7. Conclusions

The Comprehensive Assessment of Water Management in Agriculture highlights the urgent need for new water management investments in agriculture to meet future food demands, in light of increasing pressure on water resources and uncertainty due to climate change. Rainfed agriculture will continue to play a dominant role in providing food and generating livelihoods, particularly in poor countries. The global hotspots in terms of water, food and livelihoods are in the dryland regions; i.e., the savannah and steppe regions. Policy goals in those areas must include: (1) doubling agricultural productivity with existing water resources; (2) improving knowledge and implementing affordable strategies to achieve potential levels of land and water productivity; and (3) conducting more research on the potential cascading effects on watershed and basin scales, due to large-scale adoption of agricultural water technologies.

Upgrading rainfed agriculture in the world's water hotspots during the next 50 years will require the same level of concerted water governance and management priorities given to irrigated agriculture during the previous 50 years. This will include efforts involving institutional capacities, policy frameworks, knowledge generation, and finance. The current lack of governance, management, and investment priorities given to upgrading rainfed agriculture in developing countries often is justified by the "marginal" potential in rainfed areas and the major water scarcity problems in "dryland" areas. However, water constraints are not always related to absolute water shortage, but rather to the variability of supply. Water management to bridge dry spells can greatly reduce risks. Low yields and low water productivity due to large, non-productive water flows offer windows of opportunity, which can be realized by implementing a new approach to IWRM that encompasses both green and blue water resources from the catchment to basin scale.

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