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Improving water use in tropical rain-fed systems: the situation in India

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1 Introduction: the challenge of achieving global food security

Providing global food security for an ever-growing population, predicted to reach nine billion by 2050, and reducing poverty are challenging tasks. Growing per capita income in the emerging giant economies such as Brazil, Russia, India, China and South Africa (BRICS) means increased pressure on global food production due to changing food habits. This increased food production has to be met using finite water and land resources. The quantity of available water and land has not increased since 1950, but the availability of water and land per capita has declined significantly due to an increased global human population. For example, in India, per capita water availability has decreased from 5177 m^3 in 1951 to 1625 m^3 in 2011 due to the population increasing from 361 million in 1951 to 1.15 billion in 2011, which is expected to rise to 1.39 billion by 2025 and 1.64 billion by 2050, with an associated decrease in per capita water availability of 1345 m^3 in 2025 and 1140 m^3 by 2050 (Wani et al., 2012). The distribution of water and land resources varies in different countries and regions of the world, and the current population is expected to increase rapidly. In this chapter, we analyse the current status of agricultural water use in tropical rain-fed areas, assess the potential and propose a new paradigm to manage agricultural water efficiently by adopting various land, water, nutrient and crop management technologies.

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2 Finite and scarce freshwater resources

Water is a natural and finite resource that circulates through the hydrological cycle of evaporation, transpiration and precipitation, mainly driven by various climatic and land management factors (Falkenmark, 1997). The total water on earth is 1385.5 million km^3 (Shiklomanov, 1993), out of which 97.3% is oceanic salt water. Fresh water constitutes only 2.7% of the total global water resource and is the lifeline of the biosphere where forest, woodlands, wetlands, grasslands and croplands are the major biomes (Postel et al., 1996; Rockström et al., 1999). Rockström et al. (1999) reported that approximately 35% of the annual precipitation (110 305 km^3) falling onto the earth's surface returns back to the ocean as surface run-off (38 230 km^3) and the remaining 65% is converted into water vapour flow. Moreover, major terrestrial biomes, that is, forest, woodlands, wetlands, grasslands and croplands together consume almost 98% of the global green water flow and generate essential ecosystem services (Rockström et al., 1999; Rockström and Gordon, 2001). The availability of fresh water, which is required to produce a balanced food diet (i.e. 3000 kcal $person^{-1}$ d^{-1}), under existing conditions and with increasing population pressure is an important concern. It is estimated that, on average, 6700 and 15 100 km^3 y^{-1} consumptive fresh water is used by croplands and grasslands, which generate food and animal protein for feeding humanity, respectively (Rockström and Gordon, 2001); this combined quantity is 30% of the earth's total green water flux.

Water availability in croplands and grasslands is becoming scarce due to increasing population pressure and changing food habits (Rockström et al., 1999, 2009). Figure 1 shows present and anticipated future food demand (Fig. 1a) in developing and developed countries, and the corresponding total freshwater requirement (Fig. 1b for developing countries and Fig. 1c for the entire globe), also considering the current trend of water productivity (WP) continued into the future (Rockström et al., 2007). It is anticipated that the total food demand in 2050 will reach approximately 11 200 million tons and out of that, 9300 million tons of food will be required for developing countries (Rockström et al., 2007; de Fraiture et al., 2007; Khan and Hanjra, 2009; Hanjra and Qureshi, 2010). With limited availability of fresh water and other resources, it is not possible to meet the future freshwater demand and therefore it is essential to enhance resource use efficiency (land, water, energy, etc.).

2.1 Green and blue water

Water resources are classified into green and blue water resources (Falkenmark, 1995), and rainfall is partitioned into blue and green water resources via important hydrological processes. Green water is the large fraction of precipitation that is held in the soil and is available for plant consumption on-site, and it returns to the atmosphere through the process of evapotranspiration (ET). The process by which a fraction of green water is consumed by plants is known as transpiration and the process through which an amount of green water returns back to the atmosphere directly from water bodies and the soil surface is known as evaporation. Blue water is the portion of precipitation which enters streams and lakes, and also recharges groundwater reserves. Humans can consume blue water directly for domestic and industrial use, and also for food production off-site (away from the area it originates).

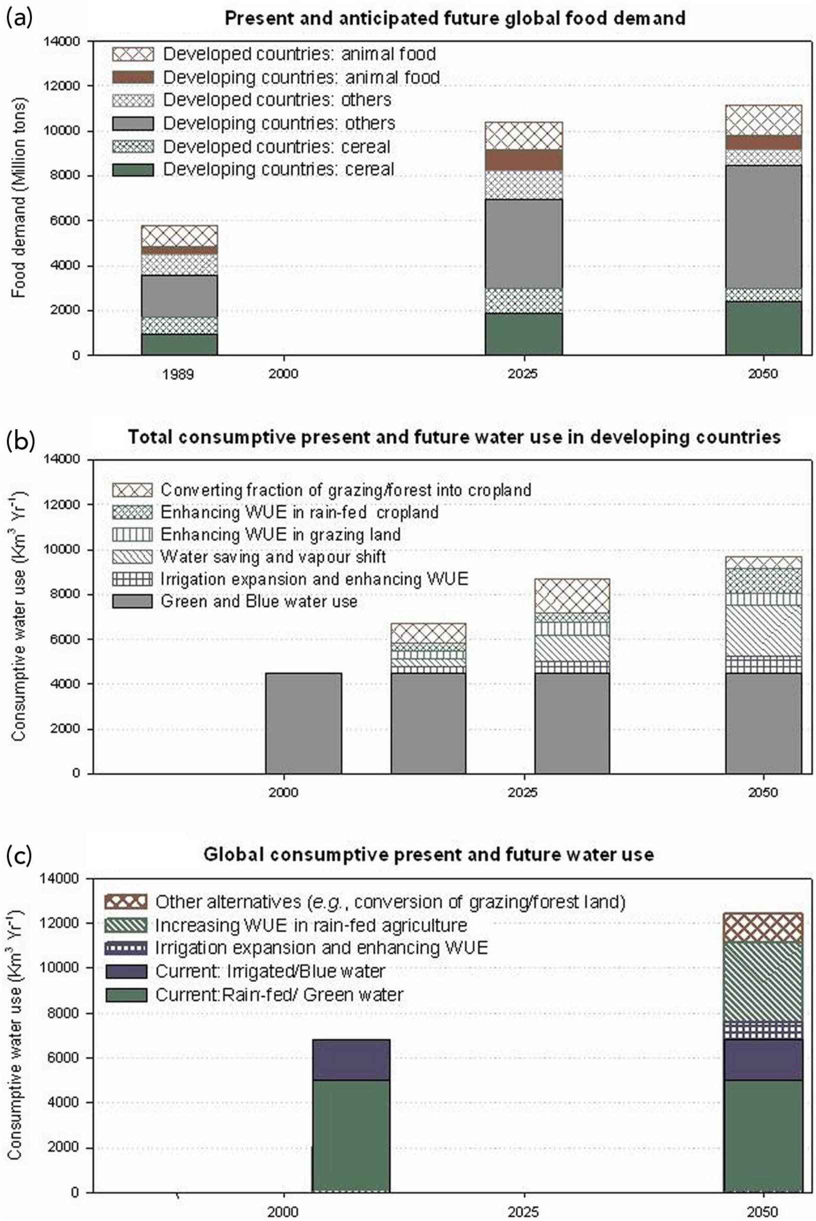

Figure 1 (a) Present and anticipated future global food demand; present and future fresh water required for food production and possible source to fill the gap in demand; (b) in developing countries and (c) both in developing and developed countries (Source: Rockström et al., 2007; de Fraiture et al., 2007; Khan and Hanjra, 2009; Hanjra and Qureshi, 2010; Wani et al., 2012).

The contribution of green water in generating global food production is very high, as nearly 85% of the total consumptive freshwater use in cropland and 98% in grassland is from green water only (Rockström et al., 1999; Rost et al., 2008; Hoff et al., 2010). Despite this, traditionally, the emphasis of water management was mainly towards blue water resources (Molden, 2007; Falkenmark and Molden, 2008), and green water was largely ignored (Wani et al., 2009, 2011a,b). Under present scenarios, the available blue water in most of the river basins has been harvested and allocated for different sectors, and hence, further expanding irrigated areas using surface water has limited scope. In such a scenario, most of the future food production is expected to come from rain-fed areas as they have large untapped potential.

2.2 Freshwater resources in India

Out of the annual average precipitation of 4000 km^3 across the country, 1120 km^3 is partitioned into blue water (690 and 430 km^3 surface and groundwater resources, respectively) and the remaining 2880 km^3 is available as green water. Land use of India in the year 2011/12 shows that 54% of the total geographical area is cultivable, 21% is under forest, 16% is under wasteland and in the fallow category and 13% is in other use and not available for cultivation. At present, a total of 142 million hectare (Mha) (43% of the total geographical area) is under agricultural use; within that, 47% of croplands is irrigated and 53% is under rain-fed farming.

Between 1950 and 2010, the gross cultivated area (rain-fed and irrigated) increased from 130 to 195 Mha (Fig. 2a), whereas the net sown area has remained almost constant (142 Mha in the current situation) since the early 1960s. The cropping intensity of the current production system is 139%, whereas that of the irrigated area has increased from 17% to 47% (0.78% expansion per year) over 60 years. Figure 2b shows the source-wise total irrigated area and its change during the period between 1950–1951 and 2010–2011. The net irrigated area in India has significantly increased from 21 Mha in 1950/51 to more than 66 Mha in 2012/13. Canals, surface tanks (smaller water bodies) and open wells were the major sources of water until the 1970–80s. With the development of pumping technology and rural electrification, large-scale groundwater extraction started after the 1970s. Currently, nearly 60% of the total irrigated area in the country is dependent upon the groundwater resource (Fig. 2b). The total annual groundwater availability in India is estimated to be 430 billion cubic metres (bcm) and the annual draft is 300 bcm. Due to over extraction of groundwater, many regions in the country are classified under the critical and overcritical category (GoI, 2013).

In addition, climate change is a major challenge faced by agriculture in India, more so in the semi-arid tropics (SAT). In recent years, natural and anthropogenic factors have influenced climate variability and contributed to a large extent to climate change. Rao et al. (2013) found that the semi-arid area increased by 8.45 Mha in India (mainly in five states, *viz*. Madhya Pradesh, Bihar, Uttar Pradesh, Karnataka and Punjab) and decreased by 5 Mha in 11 states between 1971–1990 and 1991–2004, contributing to an overall increase in SAT area of 3.45 Mha (Fig. 3). In addition, there has been a net reduction of 10.71 Mha in the dry subhumid area. Furthermore, the study has indicated that dryness and wetness are increasing in different parts of the country replacing moderate climates which previously existed in these regions (Rao et al., 2013).

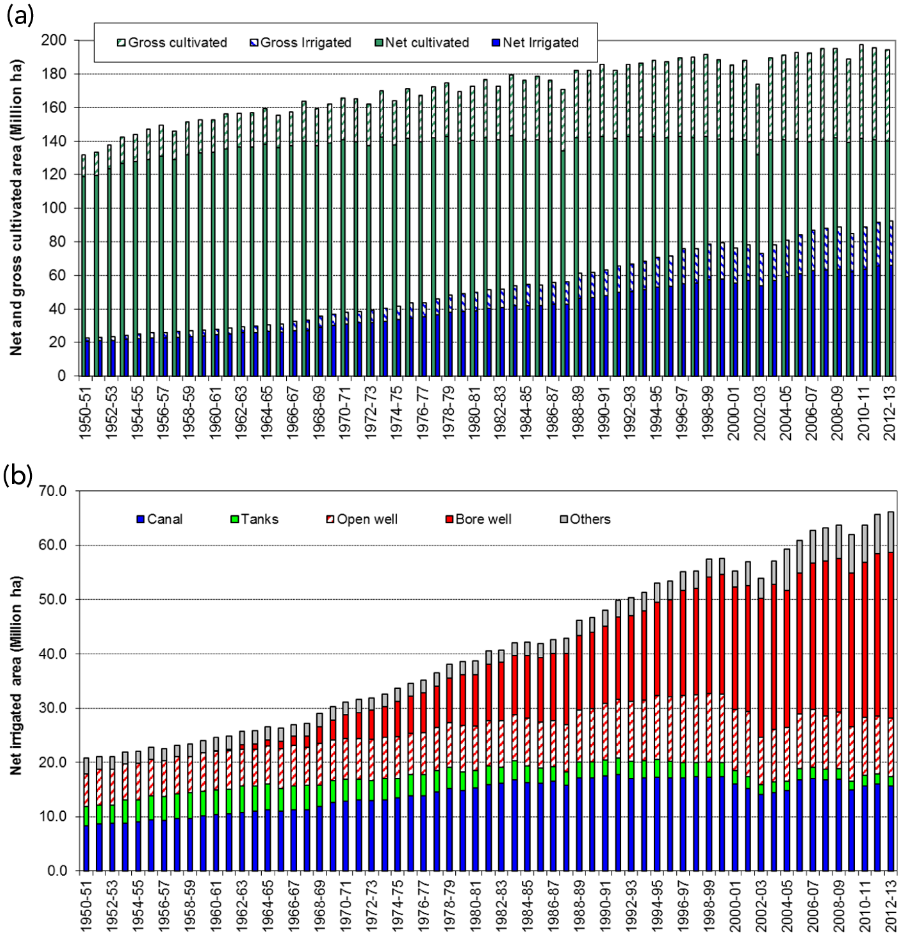

Figure 2 (a) Net and gross cultivated area; (b) source-wise net irrigated area in India between 1950/51 and 2012/13 (Source: Government of India, 2014).

3 Rain-fed agriculture: an overview

3.1 Current status and importance

Eighty per cent of the cultivated area worldwide is rain-fed and contributes to nearly 60% of the world's food production (Wani et al., 2012b). In India, the rain-fed cropped area comprises 53% of the total agricultural land, that is, 75 Mha (Fig. 2a). A large fraction of canal command areas has reached a plateau in terms of productivity, and there is a growing concern with regard to feeding a rapidly growing population. The option of increasing arable land has been exhausted, and there are limited opportunities for irrigation expansion.

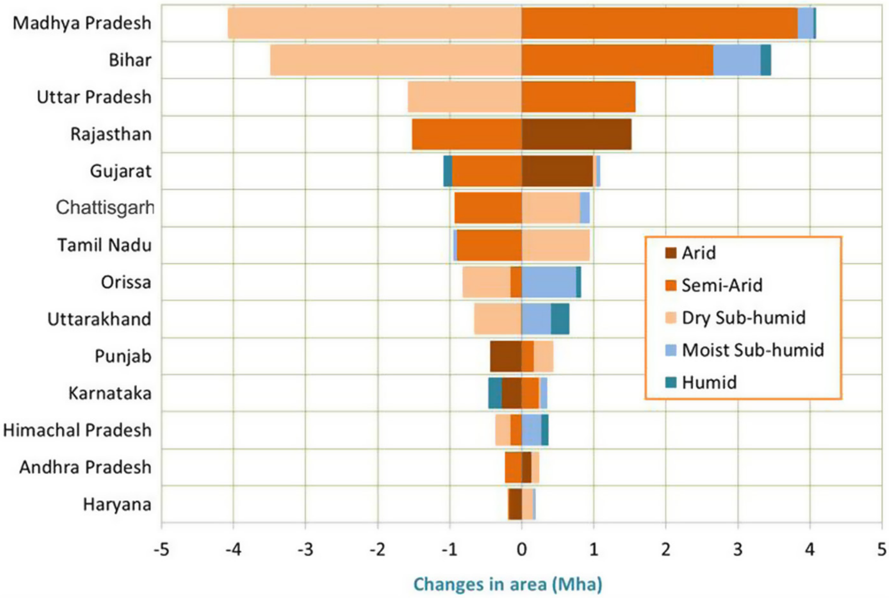

Figure 3 Change in agro-climatic regions in India between 1971–90 and 1991–2004 (Rao et al., 2013).

However, evidence shows that a large yield gap exists in Asia and Africa between current productivity and achievable potential, with farmers' yields being a factor of twofold to fourfold lower than the achievable yields (Wani et al., 2003a,b; Rockström et al., 2007). Studies involving rain-fed agriculture show opportunities for enhancing food production through enhanced WP by adopting appropriate soil, water and crop management options (Wani et al., 2009). The vast potential of rain-fed agriculture needs to be unlocked through knowledge-based management of soil, water and crop resources to increase productivity and water use efficiency (WUE) through sustainable intensification.

3.2 Potential for enhancing WUE

A linear relationship is generally assumed between biomass growth and vapour flow (ET), which describes WP ranging between 1000 and 3000 m^3 t^{-1} for grain production (Rockström, 2003). It is recognized that this linear relationship does not apply for the lower yield, up to 3 t ha^{-1}, which is the yield level of small-scale and marginal-scale farmers in dry land/rain-fed areas. The reason is that improvements in agricultural productivity, resulting in increased yield and denser foliage, will involve a vapour shift from non-productive evaporation (*E*) in favour of productive transpiration (*T*) and a higher *T*/*ET* ratio as transpiration increases (essentially linearly) with a higher yield (Stewart et al., 1975; Rockström et al., 2007). Huge scope for improving WUE by green water management, especially at the lower yield range, exists and can help reduce the water stress situation.

Evidence from water balance analyses of farmers' fields around the world shows that only a small fraction, less than 30% of rainfall, is used as productive green water flow (plant transpiration) supporting plant growth (Rockström, 2003). In arid areas, as little as

10–15% of the rainfall is typically consumed as productive green water flow (transpiration) and 85–90% flows as non-productive evaporation, that is, no or very limited blue water generation (Oweis and Hachum, 2001). In temperate arid regions, such as West Africa and North Africa, a large portion of the rainfall is generally consumed by farmers' fields as productive green water flow (45–55%), resulting in higher yield levels (3–4 t ha^{-1} compared with 1–2 t ha^{-1}), 25–35% of the rainfall flows as non-productive green water flow and the remaining 15–20% generates blue water flow. Agricultural water management interventions in the watershed in the Indian SAT converted more rainfall into green water and also reduced the amount of run-off by 30–50%, depending on rainfall amount and distribution (Garg et al., 2011).

There is vast untapped potential in rain-fed areas using appropriate soil and water conservation practices (Rockström and Falkenmark, 2000; Wani et al., 2003a, 2009, 2011, 2011a; Rockström et al., 2007, 2010; Anantha and Wani, 2016). Even in tropical regions, particularly in the subhumid and humid zones, agricultural yields in commercial rain-fed agriculture exceed 5–6 t ha^{-1} (Rockström and Falkenmark, 2000; Wani et al., 2003a, 2003b). At the same time, the dry subhumid and semi-arid regions have experienced the lowest yields improvements per unit land. Here, yields oscillate between 0.5 and 2 t ha^{-1}, with an average of 1 t ha^{-1} in sub-Saharan Africa (SSA) and 1–1.5 t ha^{-1} in South Asia, Central Asia, West Asia and North Africa under rain-fed agriculture (Rockström and Falkenmark, 2000; Wani et al., 2003a,b).

Data obtained from long-term experiments conducted at ICRISAT's heritage watershed site (Fig. 4) have shown that due to Integrated Water Resources Management (IWRM) interventions, the average crop yield is fivefold higher than that by traditional farming practices (Wani et al., 2003a, 2011a,b). Similar results were also recorded at Adarsha

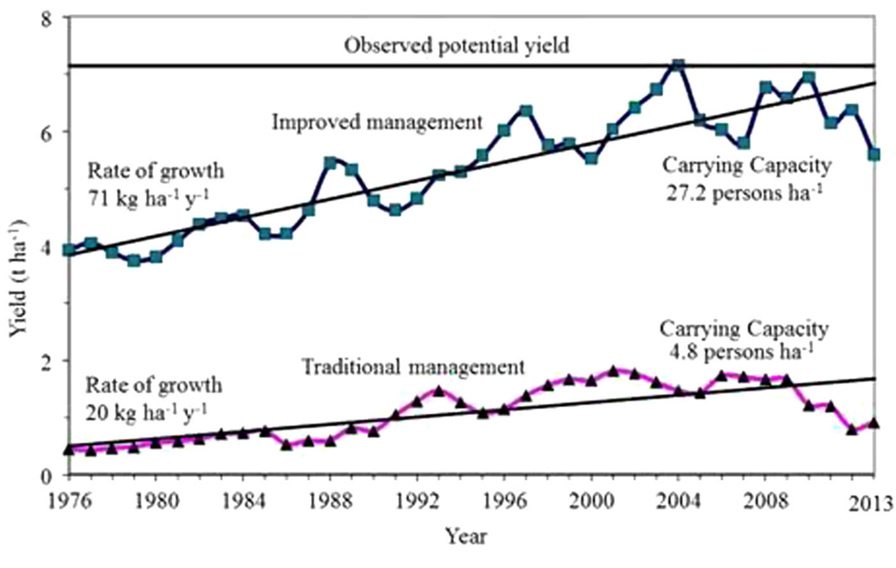

Figure 4 A comparison of harvested grain yield by implementing IWRM techniques in the BW1 Vertisols heritage watershed at ICRISAT with traditional farmer's practices at BW4C; results are shown from 1976 onwards.

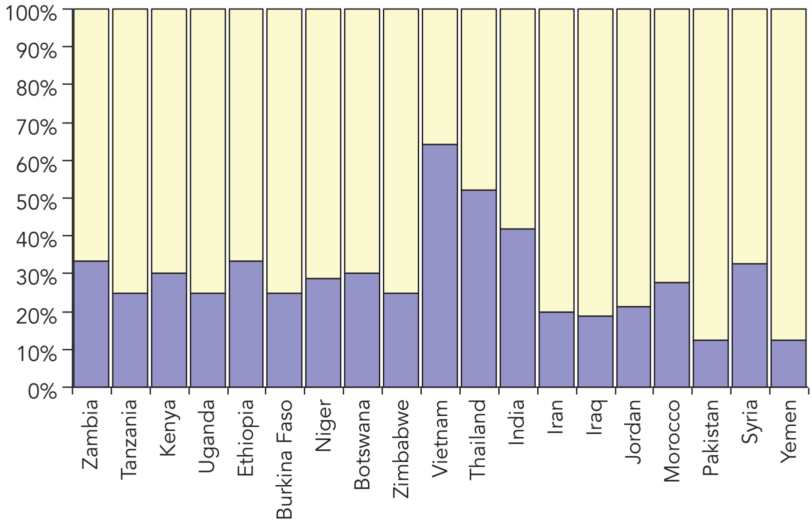

Figure 5 Examples of observed yield gap (for major grains) between farmers' yields and achievable yields (100% denotes achievable yield level and columns show the actual observed yield levels) (Source: Rockström et al., 2007).

watershed, Kothapally, Southern India, where implementing IWRM interventions enhanced crop yields almost twofold to threefold than those in the baseline situation (Wani et al., 2003a; Sreedevi et al., 2004; Karlberg et al., 2015).

Yield gap analyses carried out for major rain-fed crops in semi-arid regions in Asia and Africa and rain-fed wheat in West Africa and North Africa revealed large yield gaps which were a factor of twofold to fourfold lower than achievable yields (Fig. 5). Detailed yield gap analysis for major rain-fed crops in different parts of the world has been reported (Singh et al., 2009; Fisher et al., 2009). In many countries in West Asia, farmers' yields are less than 30% of achievable yields, while in some Asian countries the figure is closer to 50%. Historic trends present a growing yield gap between farmers' practices and farming systems that can benefit from advances in management practices (Wani et al., 2003b, 2009, 2011a).

4 Measures to enhance WUE: overview and soil nutrient management

4.1 Overview

WUE and WP are interchangeably used in the literature, but there is a slight difference. WUE is the ratio of water supplied to the plant to that effectively taken up by the plant (i.e. not lost to drainage, bare soil evaporation or interception). Ragab Ragab (2014) defined WP as production per unit application of water both under rain-fed and irrigated conditions. This can be achieved by 1) increasing the marketable yield of the crops for each unit of water transpired, 2) reducing the outflows/losses or 3) enhancing the effective use of rainfall, water stored in the soil and the marginal quality of water (Ragab Ragab, 2014). The first option refers to the need to improve crop yield, the second one intends to increase the beneficial use (water uptake – transpiration) of water supply against non-beneficial losses (evaporation) and the third aims to efficiently utilize water resources, including water diverted from reservoirs, streams or groundwater sources. All these options improve on-farm management aspects of crop growth, through the application of best crop management practices which will permit less use of water for irrigation, decrease evaporation losses, optimize fertilizer supply, allow better pest control, minimize energy consumption and improve soil conditions. This is of particular importance in arid and semi-arid regions with limited water availability, where farmers frequently have to apply deficit irrigation strategies and manage water supply in accordance with the sensitivity of the crop's growing stages to water stress. In those situations, the increase of WUE would lead to better WP and would be in the farmer's interest to improve economic return from investing in an irrigation water supply (Ragab Ragab, 2014).

4.2 Test-based soil nutrient management

Given the competition for water and uncertainties associated with climate change, improving WUE in rain-fed agriculture needs to be a primary focus. Land degradation in rain-fed regions is a major factor, which compromises the ability of crop plants to effectively utilize available water in food production. Due to prolonged nutrient mining, dry lands are depleted of not only the primary nutrients like nitrogen (N), phosphorus (P) and potassium (K) but also secondary and micronutrients like sulphur (S), zinc (Zn), iron (Fe) and boron (B) (Wani et al., 2012a, 2015a,b; Sahrawat et al., 2010; Chander et al., 2013a,b, 2014, 2016), and other nutrient deficiencies are also emerging. Nutrient deficiencies in India across different states are as high as 11–76% for nitrogen [deduced from soil organic carbon (C)], 21–74% for P, 1–24% for K, 6–96% for S, 56–100% for B and 8–85% for Zn (Table 1). Most farmers are not aware of secondary and micronutrient deficiencies and thus their general practice is to add fertilizers containing only macronutrients [nitrogen–phosphorus–potassium (NPK)] in suboptimal or indiscriminate amounts, which creates a nutrient imbalance, leading to increased land degradation.

Table 1 Soil fertility degradation of farmers' fields across different states in India

		% field deficiency of available nutrients				
State	% Fields with low soil organic C	P	K	S	B	Zn
Andhra Pradesh	76	38	12	79	85	69
Gujarat	12	60	10	46	100	85
Karnataka	52	41	23	52	62	55
Kerala	11	21	7	96	100	18
Madhya Pradesh	22	74	1	74	79	66
Rajasthan	38	45	15	71	56	46
Tamil Nadu	57	51	24	71	89	61

Source: Wani et al., 2012a, 2015a.

Nutrient deficiency and soil test-based fertilizer application

Various on-farm studies corroborate the benefits of applying fertilizers to soils deficient in secondary and micronutrients in order to effectively utilize the available water and obtain higher crop yields (Chander et al., 2013b, 2016). Along with nutrients, low soil organic carbon in rain-fed regions poses challenges for the efficient use of water resources (Table 1). The impact of soil C positively affects the physical properties as it absorbs more rainfall which is available for later crop use and results in higher WP. Soil organic C also influences the ability of soils to retain nutrients and microbial biomass activity and is a major source of nutrients, which altogether exert a positive effect on crop growth to effectively use available water. On-farm studies have shown that when a part of the nutrient requirement is met through recycling on-farm wastes (i.e. composts), the crop and WP are higher under such an integrated approach compared with even balanced fertilization solely through chemical fertilizers (Table 2). Thus, the management of soil organic C is important for sustainable soil management (Wani et al., 2003a).

Scaling up of soil test-based fertilizer application in Karnataka, Southern India

Realizing the importance of integrated soil–water–nutrient and crop management for sustainable food production in dry lands, the Government of Karnataka (one of the states in South India) started an innovative and large-scale mission mode project called '*Bhoochetana*' (soil rejuvenation) in 2009 with the help of ICRISAT and its partners (Raju and Wani, 2016; Garg et al., 2016b; Anantha et al., 2016). This programme largely focused on soil, nutrient, land and crop management practices along with strengthening institutional capacity and creating awareness among various stakeholders. Soil analysis results from large-scale farmers' fields (~92 000) showed that the majority of the farmers' fields (52%) were low in organic carbon. In Karnataka as a whole, 41% of farms were deficient in P, indicating that 59% of farmers' field which were sufficient in P had an opportunity, through site-specific nutrient management, to cut costs by using current recommendations. Potassium as such was not a problem in the state. Across the state only 23% of the sampled fields tested low for potassium, and a science-led approach called for a reduction in K fertilizer by only applying recommended dose. Interestingly,

Table 2 Effect of nutrient management on soybean (*Glycine max*) grain yield, benefit/cost ratio and rainwater use efficiency under rain-fed conditions in Madhya Pradesh, India

District	Grain yield (kg ha^{-1})			Standard deviation, SD (5%)	Benefit/cost ratio		Rainwater use efficiency (kg mm^{-1} ha^{-1})		
	FP	BN	INM		BN	INM	FP	BN	INM
Guna	1270	1440	1580	34	1.31	4.58	1.76	1.99	2.19
Raisen	1360	1600	1600	115	1.85	3.55	1.76	2.07	2.07
Shajapur	1900	2120	2410	69	2.99	10.2	3.45	3.85	4.38
Vidisha	1130	1410	1700	640	2.16	8.43	1.48	1.84	2.22

Notes: FP = farmers' practice (application of N, P, K only); BN = balanced nutrition (FP inputs plus S + B + Zn); INM = integrated nutrient management (50% BN inputs + vermicompost). Source: Chander et al., 2013a.

the analysis revealed that most farms in Karnataka exhibited widespread deficiencies of ignored secondary and micronutrients, for example, 52% for S, 55% for Zn and 62% for B.

After realizing the potential of this approach, the programme expanded to irrigated agriculture within a short period of two years from its inception. Soil fertility assessment has been undertaken as an entry-point activity, and crop-specific soil test-based fertilizer application was recommended at the taluk level (an administrative boundary comprising a number of villages) instead of blanket recommendations followed earlier at state level, as there was indiscriminate use of fertilizer both in rain-fed and irrigated areas. This approach was adopted in a phased manner and included all 30 districts of Karnataka within a span of four years and covered 3.73 Mha comprising major dry land and irrigated crops (Wani et al., 2016, 2017).

5 Measures to enhance WUE: *in-situ* water conservation practices

5.1 Landform management

WP in Vertisols especially in Central India, remains low because of the challenge of successfully growing two crops in a year. These soils have poor hydraulic conductivity and are poorly drained. Initial downpours distort soil structure and adversely affect water infiltration into the soil, thereby negatively affecting crop and resource use efficiency, including water (Wani et al., 2015b). Three fundamental barriers that affect cropping in a black soil region are as follows: (i) the threat of flooding of the rainy season crop due to heavy rains, (ii) difficulty of soil preparation prior to the monsoon for timely sowing of a rainy season crop and (iii) reduction in available soil moisture for the post-rainy season crop if a rainy season crop is grown.

On-farm studies undertaken in Madhya Pradesh, Central India, showed that landform management coupled with balanced fertilization enabled farmers to grow and harvest good soybean yields during the rainy season (Table 3) and also increased post-rainy wheat and chickpea grain yields in rainy fallow-managed plots compared with the farmers' practice of growing only one crop (wheat or chickpea) in the post-rainy season. Therefore, landform management in Vertisols is an effective technology to use rainwater resources for increased food production.

Table 3 Effects of landform management and balanced nutrition on soybean yield during the rainy season (2010) in the fallow regions of Madhya Pradesh

		Grain yield (kg ha^{-1})			Straw yield (kg ha^{-1})		
District	Crop	CF + BN	BBF + BN	LSD (5%)	CF + BN	BBF + BN	LSD (5%)
Guna	Soybean	1350	1450	210	2110	2310	226
Raisen	Soybean	1270	1360	59	1930	2300	70
Indore	Soybean	1600	1700	231	1730	1810	158
Vidisha	Soybean	1340	1520	511	1440	1830	748
Mean	Soybean	1390	1508		1803	2063	

Notes: CF = conservation furrow at 4–5 m distance; BBF = broad-bed and furrow (1 m wide raised bed followed by 0.50 m furrow); BN = balanced nutrition (N, P, K plus S, B, Zn). Source: Wani et al., 2012.

5.2 Fallow management for crop intensification

Rice-fallow management

About 14.29 Mha of rice fallows are available in the Indo–Gangetic Plains, spread over Bangladesh, Nepal, Pakistan and India, out of which 11.4 Mha (82%) are in the Indian states of Bihar, Madhya Pradesh, Chhattisgarh, Jharkhand, West Bengal, Odisha and Assam (Subba Rao et al., 2001). A considerable amount of green water is available after the monsoon, especially in rice-fallow systems, which could easily be utilized by introducing a short-duration legume crop with simple seed priming and micronutrient modification (Subba Rao et al., 2001; Kumar Rao et al., 2008; Wani et al., 2009; Singh et al., 2010). Taking advantage of sufficient available moisture in the soil after harvesting a rice crop during the winter season in eastern India, the growing of early maturing chickpeas in rice-fallow areas with best-bet management practices (minimum tillage for chickpea, seed priming of chickpea for 4–6 h with the addition of sodium molybdate to the priming water at 0.5 g L^{-1} kg^{-1} seed and *Rhizobium* inoculation at 5 g L^{-1} kg^{-1} seed, micronutrient modification and the use of short-duration rice cultivars during the rainy season) resulted in chickpea yields of 800–850 kg ha^{-1} (Kumar Rao et al., 2008; Harris et al., 1999). An economic analysis has shown that growing legumes in rice fallows is profitable for farmers with a benefit:cost (B:C) ratio exceeding 3.0 for many legumes. In addition, utilizing rice fallows for growing legumes could result in the generation of 584 million person-days of employment for South Asia.

In a number of villages in the states of Chhattisgarh, Jharkhand and Madhya Pradesh in India, on-farm farmers' participatory action research trials sponsored by the Ministry of Water Resources, Government of India, showed a significantly enhanced rainwater use efficiency through cultivation of rice fallows with a total production of 5600–8500 kg ha^{-1} for two crops (rice + chickpea), benefiting the farmers with an increased average net income of Rs. 51 000–84 000 per hectare (Singh et al., 2010).

Rainy season fallow management

Vertisols and associated soils, which occupy large areas globally (approximately 257 Mha, Dudal, 1965), are traditionally cultivated during the post-rainy season on stored soil moisture resulting from waterlogging during the rainy season due to poor infiltration rates. The practice of fallowing Vertisols and associated soils in Madhya Pradesh, India, was perceived to be decreased after the introduction of soybean; however, 2.02 Mha of cultivable land is still kept fallow in Central India, during the kharif season (Wani et al., 2002; Dwivedi et al., 2003). Through on-farm participatory research, ICRISAT demonstrated the avoidance of waterlogging during the initial crop growth period on Vertisols by preparing the fields to broad-bed and furrow (BBF) along with grassed waterways. Simulation studies using the SOYGRO model showed that the early sowing of soybean in seven out of ten years was possible and could result in a threefold increase in soybean yields, in combination with appropriate nutrient management. Hence, combining timely sowing with short-duration soybean genotypes would pave the way for a successful post-rainy season crop as the moisture carrying capacity was sufficiently high to support it. On-farm soybean trials conducted by ICRISAT involving improved land configuration (BBF) and short-duration soybean varieties along with fertilizer application (including micronutrients) showed a yield increase of 1300–2070 kg ha^{-1} compared with 790–1150 kg ha^{-1} in the

Guna, Vidisha and Indore districts of Madhya Pradesh, Central India. Increased crop yields (40–200%) and incomes (up to 100%) were possible with landform treatment, new varieties and other best-bet management options (Wani et al., 2008).

Minimum tillage or conservation agriculture

There is a direct relationship between consumptive water use (ET) and crop yield. ET comprises two major processes: non-productive evaporation and productive transpiration. Evaporation, however, cannot be completely avoided but could be minimized through various field-scale management practices such as conservation agriculture (CA). Conservation tillage, an essential component of CA, constitutes land cultivation techniques which attempts to reduce labour, promote soil fertility and enhance soil moisture conservation. CA is now recognized as the missing link between sustainable soil management and reduced labour cost, especially during land preparation, and holds the potential to increase crop production and reduce soil erosion.

Studies conducted in the semi-arid regions of Africa and Asia indicated that by adopting CA techniques in Tanzania's Bukoba and Missenyi districts of the Kagera Region, the average maize yield from smallholder farmers increased from 2.50 t ha^{-1} to 3.40 t ha^{-1} (Kajiru and Nkuba, 2010). Tanzania has been fostering the adoption of CA because of its potential to address three areas of crucial importance to smallholder farmers, that is, demand on household labour, food security through increased and sustainable crop yields and household income (Mariki, 2004; Lofstrand, 2005). Some form of CA is practised on 40% of the rain-fed farmlands in the United States and is also becoming popular in several Latin American countries (Derpsch, 2005; Landers et al., 2001). Examples from SSA show that converting from plough to CA resulted in yield improvements ranging between 20% and 120%, with WP improvement ranging from 10% to 40% (Rockström et al., 2009). In northern China, on the Loess Plateau, CA increased wheat productivity and WUE by up to 35% compared with conventional tillage, especially in the low rainfall years, suggesting benefits of CA in the dry farming areas of northern China (Li Hong Wen et al., 2007; Wang et al., 2007). For the best results, CA practices such as mulching must be accompanied by requisite agronomic practices such as the use of fertilizers, manures, pesticides and high-quality seeds, as well as proper water application and management. The potential disadvantages of CA are higher costs of pests and weed control, the cost of acquiring new management skills and investment in new planting equipment. CA can be practised on all soils, especially light soils. It increases productivity, sustainability and the efficient use of natural resources (Rockström et al., 2009). Straw tends to be used for animal feed in most parts of the SAT, particularly in India, Senegal and Mali. Therefore, while mulches appear to be useful theoretically, from a practical point of view it is difficult to see how they can be used in the present conditions of SAT agriculture. It is even debatable if production of more biomass through breeding will induce farmers in the region to apply residue to their soils or induce them to sell their extra residues in view of the attractive prices offered for fodder during the dry season.

Direct seeded rice

Generally, the manual transplanting of rice after 2–3 puddling operations with 21- to 35-day-old rice seedlings is a common practice in Asia. This age-old method of planting is used to reduce water percolation and also helps in weed control. However, this system is water-consuming and labour-intensive which results in a higher cost of cultivation. On the other hand, machine-sown dry direct seeded rice (DSR) is a modern agricultural technology that allows rice seeds to be sown directly into non-puddled fields, forgoing the need for rice nurseries and the transplantation of seedlings. DSR generally requires one or two passes of the machine and can also be practised under zero tillage, offering considerable time, cost and energy savings for farmers.

Farmers' participatory field demonstrations of DSR in Karnataka, South India, showed the following benefits of DSR over the transplanted method of rice cultivation.

- Reduced cost of cultivation (22 000–25 000 ha^{-1}) by avoiding ploughing, puddling and transplanting operations
- Facilitates a timely establishment of rice that would provide an opportunity to cultivate a second crop in the post-rainy season
- Saves 40–60% water (irrigation frequency in DSR = once in a week; irrigation frequency in a transplanted paddy = alternate days)
- Saves energy, labour, fuel and seed requirements
- Yields are equal to or higher than those with a transplanted paddy (6–7.5 t ha^{-1}).

6 Measures to enhance WUE: irrigation management

6.1 Supplemental irrigation

In semi-arid and subhumid agroecosystems, dry spells occur in almost every season. These dry spells need to be mitigated to save the crop from drought and minimize the climate risks to crop production in rain-fed systems. Supplemental irrigation is also used to secure harvests or to provide irrigation to the second crop during the post-rainy season. The efficient use of water involves both the timing of crop irrigation and efficient water application methods. Broadly, the methods used for application of irrigation water can be divided into two types, *viz*. surface irrigation systems (border, basin and furrow) and pressurized irrigation systems (sprinkler and drip). In the surface irrigation system, the application of irrigation water can be divided into two parts: (1) conveyance of water from its source to the field and (2) application of water in the field.

In most SAT areas, the water is carried to cultivated fields through open channels, which are usually unlined and therefore, a large amount of water is lost through seepage. Vertisols generally need no lining of the open field channels as the seepage losses in these soils are low mainly due to the low saturated hydraulic conductivity, in the range of 0.3–1.2 mm h^{-1} (El-Swaify et al., 1985). For Alfisols and other sandy soils, with more than 75% sand, the lining of an open field channel or use of irrigation pipes is necessary to reduce the high seepage water losses. The use of closed conduits (plastic, rubber, metallic and cement pipes) is becoming popular, especially with farmers growing high-value crops, *viz*. vegetables and horticultural crops (Pathak et al., 2009).

The formation of deep, wide cracks during soil drying is a common feature of Vertisols. The abundance of cracks is responsible for high initial infiltration rates (as high as 100 mm h^{-1}) in dry Vertisols (El-Swaify et al., 1985). This specific feature of Vertisols makes the efficient application of limited supplemental water to the entire field a difficult task.

Compared with a narrow ridge and furrow, the BBF system saved 45% of the water without affecting crop yields on Vertisols. Compared with a narrow ridge and furrow and flat systems, the BBF system had higher WP and water distribution uniformity and a better soil wetting pattern (Pathak et al., 2009). Studies conducted to evaluate the effect of shallow cultivation in furrow on the efficiency of water application showed that the rate of water advance was substantially higher in cultivated furrows compared with that in uncultivated furrows. Shallow cultivation in moderately cracked furrows, before the application of irrigation water, reduced the water required by about 27% with no significant difference in chickpea yields. Similarly, increased crop yields through supplemental irrigation were observed for field experiments and also on-farm farmers' participatory field trials in Asia and Africa (Table 4).

6.2 Deficit irrigation

Impressive benefits were reported upon the supplemental irrigation of rainy and post-rainy season crops on Alfisols at ICRISAT, Patancheru, India (El-Swaify et al., 1985; Pathak and Laryea 1991). The average WP for sorghum (14.9 kg mm^{-1} ha^{-1}) was more than that for pearl millet (8.8–10.2 kg mm^{-1} ha^{-1}) (Table 5). An intercropped pigeonpea responded less well to irrigation, and its average WP ranged from 5.3 to 6.7 kg mm^{-1} ha^{-1} for both sorghum/pigeonpea and pearl millet/pigeonpea intercrop systems. Tomato responded very well to water application with an average WP of 186.3 kg mm^{-1} ha^{-1} (Table 5). For the sorghum/pigeonpea intercrop, two irrigations of 40 mm each gave an additional gross return of US$217 ha^{-1}. The highest additional gross return of US$1296 ha^{-1} from supplemental irrigation was obtained with tomato.

Table 4 Impact of supplemental irrigation on crop yield

Pilot location	Crop	Irrigation applied (cm)	Control (t/ha)	Treated (t/ha)	Yield increase (%)
Sahel, Africa	Sorghum	2	0.45	1.4	210
Jhansi, India	Sorghum	3	0.38	2.51	15
Jhansi, India	Maize	1	2.31	2.66	40
Bengaluru, India	Maize	2	3.16	4.43	43
Indore, India	Finger millet	5	1.56	2.23	14
Jhansi, India	Castor	5	1.01	1.32	240
Jhansi, India	Pigeonpea	3	0.05	0.17	560
Dantiwada, India	Pigeonpea	5	0.05	0.33	58
Dehradun, India	Wheat	2	1.17	1.58	78
Dehradun, India	Wheat	6	1.17	2.6	40
Ranchi, India	Rape seed	1	0.25	0.35	84

Table 5 Grain yield response of cropping systems to supplemental irrigation on an Alfisols watershed at ICRISAT, Patancheru, Andhra Pradesh, India, 1981–82

Yield with irrigation (kg ha^{-1})	Yield increase (kg ha^{-1})	WP (kg ha^{-1} mm^{-1})	Yield with irrigation (kg ha^{-1})	Yield increase (kg ha^{-1})	WP (kg ha^{-1} mm^{-1})	Combined WP (kg ha^{-1} mm^{-1})
Intercropping system						
Pearl millet			Pigeonpea			
2353	403	10.0	1197	423	5.3	6.8
Sorghum			Pigeonpea			
3155	595	14.9	1220	535	6.7	9.4
Sequential cropping system						
Pearl millet			Cowpea			
2577	407	10.2	735	425	5.3	6.9
Pearl millet			Tomato			
2215	350	8.8	26 250	14 900	186.3	127.1

Source: Pathak and Laryea (1991). Irrigation of 40 mm each was applied.

The best responses to supplemental irrigation were obtained when irrigation water was applied at critical stages of the crop. To get the maximum benefit from the available water, growing high-value crops (*viz*. vegetables and horticultural crops) is becoming popular even with poor farmers (Pathak et al., 2009). According to Oweis (1997), supplemental irrigation of 50–200 mm can bridge critical dry spells and stabilize yields in arid to dry subhumid regions; however, 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 have indicated that supplemental irrigation systems are affordable by small-scale farmers (Fan et al., 2000; Fox et al., 2005). However, policy framework, institutional structure and human capacity, similar to those for a full irrigation infrastructure, are required to successfully apply supplemental irrigation in rain-fed agriculture.

6.3 Need-based irrigation application

In general, farmers practise calendar-based irrigation scheduling that results in over irrigation and poor WUE. Due to inherent variability of bio-physical (soil hydraulic parameters, soil depth, etc.), topographical and land management (cropping sequence, time of sowing, etc.) factors, calendar-based irrigation scheduling does not always match with crop water requirement, resulting in reduced crop yield and poor WUE. Therefore, it is necessary to follow a need-based water application to optimize the available water resources. A decision support system called the 'Water Impact Calculator' (WIC) was developed at ICRISAT using strategic data collected at its research station (Garg et al., 2016a).

An ICRISAT-led consortium with local partners, non-governmental organizations and an irrigation company (Jain Irrigation Ltd.) evaluated the WIC by conducting farmer participatory field trials between 2010 and 2014 at different sites in India (e.g. Mota Vadala in Jamnagar, Gujarat; Kothapally in Ranga Reddy, Telangana; Parasai-Sindh watershed, Jhansi; Dharola Tonk, Rajasthan and the ICRISAT research station). Irrigation was scheduled using WIC calculations and an exact quantity of water was applied as per the recommendations. The gravimetric soil moisture content was measured at 0–15 cm, 15–30 cm, 30–45 cm and 45–60 cm soil depths at weekly intervals. Crop grain yield and above-ground biomass yield were estimated at the end of the crop harvest. WIC-simulated soil moisture was compared with measured data at different soils and rainfall regions. In general, simulated soil moisture was found to be in good agreement with observed data. Based on minimum WIC inputs on soil type, soil depth, date of sowing and climatic data, the exact amount of water on specific dates was recommended in drip and flood/furrow irrigated fields. Crop yields were compared among WIC and traditionally managed fields. Farmers at pilot sites could save nearly 30% water due to need-based irrigation application (Garg et al., 2016a).

7 Future trends

As discussed, rain-fed agriculture holds huge potential to meet future food demand. To meet the challenges of the twenty-first century of producing more food from finite water and land resources, there is an urgent need to manage agricultural water, particularly in the developing world. Traditionally, water management has dealt with irrigated agriculture; however, as shown by the comprehensive assessment of water for food and water for life (Molden, 2007), agricultural water management is larger than irrigation and a vast untapped potential of 1.2 billion ha rain-fed agriculture needs to be harvested (Rockström et al., 2007; Wani et al., 2009). For harnessing the potential of rain-fed agriculture, a large portion of green water, which is underutilized at present, needs to be substantially improved to bridge the existing yield gap. The shift in water vapour on croplands from non-productive evaporation losses to productive ET needs to be improved and large scope exists from enhancing green WUE from 30–35% to 65–95% in rain-fed areas. Appropriate policy and institutional support for decentralized water management in rain-fed areas is urgently needed. Small- and marginal-scale farmers require incentives, and the help of policies and institutions, to slowly innovate to produce marketable surplus and invest further in sustainable intensification so that they can grow and prosper through intensifying rain-fed agriculture. The weak link of efficient knowledge/technology exchange from research and development organizations to farmers needs to be strengthened.

8 Where to look for further information

Due to changing climatic conditions, rain-fed farming has become more challenging. However, there is huge scope for meeting current and future food and fodder demands in rain-fed system through various agricultural water management interventions. Special emphasis has to be given to optimizing rain-fed systems with science-led interventions. The current water use efficiency in rain-fed systems is below 50%, which can be enhanced through various land, water, nutrient and crop management interventions. To harness the systems for improved productivity, a holistic approach has to be followed. This includes, for example, a thorough valuation of different crop cultivars as per LGP of different agro-ecological regions in addition to undertaking advance research for developing climate smart cultivars, and a decentralized approach to water harvesting such that its thresholds are defined for optimizing available water resources and balancing ecosystem trade-off between upstream and downstream areas.

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