9 Water Productivity in Rain-fed Agriculture: Challenges and Opportunities for Smallholder Farmers in Drought-prone Tropical Agroecosystems*

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Abstract

Considering the persistently growing pressure on finite freshwater and soil resources, it becomes increasingly clear that the challenge of feeding tomorrow's world population is, to a large extent, about improved water productivity within present land use.

Rain-fed agriculture plays a critical role in this respect. Eighty per cent of the agricultural land worldwide is under rain-fed agriculture, with generally low yield levels and high on-farm water losses. This suggests a significant window of opportunity for improvements. Ninety-five per cent of current population growth occurs in developing countries and a significant proportion of these people still depend on a predominantly rain-fed-based rural economy.

This chapter presents the agrohydrological rationale for focusing on water productivity in rain-fed agriculture, identifies key management challenges in attempts to upgrade rain-fed agriculture and presents a set of field experiences on system options for increased water productivity in smallholder farming in drought-prone environments. Implications for watershed management are discussed, and the links between water productivity for food and securing an adequate flow of water to sustain ecosystem services are briefly analysed. The focus is on sub-Saharan Africa, which faces the largest food-deficit and water-scarcity challenges.

The chapter shows that there are no agrohydrological limitations to doubling or even quadrupling on-farm staple-food yields, even in drought-prone environments, by producing more 'crop per drop' of rain. Field evidence is presented suggesting that meteorological dry spells are an important cause of low yield levels. It is hypothesized that these dry spells constitute a core driving force behind farmers' risk-aversion strategies. Risk aversion also contributes to the urgent soil-fertility deficits resulting from insignificant investments in fertilizers. For many smallholder farmers in the semi-arid tropics, it is simply not

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worth investing in fertilizers (and other external inputs) so long as the risk for crop failure remains a reality every fifth year and the risk of yield reductions every second year. These high risks are associated with periodic water scarcity during the growing season (i.e. not necessarily cumulative water scarcity).

Results are presented from on-farm agrohydrological field research with innovations in water harvesting and conservation tillage among smallholder farmers in semi-arid rain-fed farming systems. These results indicate that upgrading rain-fed production systems through supplemental irrigation during short dry spells can lead to large increases in water productivity. Downstream implications of increased upstream withdrawals of water for upgrading of rain-fed food production are discussed.

Finally, it is argued that some of the most exciting opportunities for water-productivity enhancements in rain-fed agriculture are found in the realm of integrating components of irrigation management within the context of rain-fed farming, e.g. supplemental or microirrigation for mitigating the effects of dry spells. Combining such practices with management strategies that enhance soil infiltration and improving water-holding capacity and the potential of water uptake of plants can have a strong impact on agricultural water productivity. This suggests that it is probably time to abandon the largely obsolete distinction between irrigated and rain-fed agriculture, and instead focus on integrated rainwater management.

Introduction: a Broadened Water-management Approach

The sheer magnitude of future food needs, to be met by production systems depending on a finite freshwater resource, indicates the necessity to focus on water productivity in both irrigated and rain-fed agriculture. However, there are several reasons why special attention should be given to rain-fed agriculture. Almost all population growth (95%) takes place in tropical developing countries, and it is also there that the bulk of present undernutrition occurs. In sub-Saharan Africa, over 60% of the population depends on rain-based rural economies, generating in the range of 30–40% of the countries' gross domestic product (GDP) (World Bank, 1997). Rain-fed agriculture worldwide is practised on approximately 80% of the agricultural land (the remaining 20% is under irrigated agriculture). This proportion varies substantially between tropical regions, from approximately 95% in sub-Saharan Africa to 65% in Asia (FAOSTAT, 1999). Rain-fed agriculture will remain the dominant source of food production during the foreseeable future (Parr *et al.*, 1990). Yields from rain-fed agriculture are often low, generally around 1 t ha^{-1} in semi-arid tropical agroecosystems (Rockström, 2001), and this fact explains why rain-fed agriculture is estimated to contribute only some 60% of the world crop production (FAO, 2002). There is ample evidence to suggest that the low productivity in rain-fed agriculture is due more to suboptimal performance related to management aspects rather than to low physical potential (Agarwal and Narain, 1997; Benites *et al.*, 1998; Rockström and Falkenmark, 2000; SIWI, 2001). This means that in the developing countries with the most rapid population growth, dependence on rain-fed agriculture operating at suboptimal level is high. Furthermore, it has been estimated that there is limited new land to be put under agriculture (McCalla, 1994; Young, 1999), contrary to the last three decades, when the bulk of increased food production in, for example, sub-Saharan Africa came from expansion of agricultural land. There is thus a growing pressure to increase agricultural productivity through raised yields per unit soil and unit water.

In this chapter, water productivity (WP) broadly signifies the efficiency of water use at the production system or farm level. At this scale, the production of more economic biomass per unit of water is expressed both in terms of more crop per unit evapotranspiration (ET) (which includes a shift from non-productive evaporation to productive transpiration without external hydrological implications) and in terms of more crop per unit rainfall or even per unit harvested water (e.g. rain plus harvested run-on surface flow). The latter involves soil and water management with possible implications for downstream accessibility of water. Downstream access to water as a result of increased water withdrawals upstream is an issue of concern, but it is assumed here that there are overall gains and synergies to be made by maximizing the efficient use of every raindrop where it falls. In other words, WP improvements should be in focus for all water flowing through the landscape, from upstream to downstream, and not as is generally the case once the water has reached a perennial river downstream, usually after an erosive journey. This rationale is in line with Evanari *et al.* (1971), who showed that a larger effective volume of water in a catchment can be generated for productive agricultural use through numerous small water-harvesting structures collecting local surface runoff than by one large storage structure located downstream. Similarly, using the rationale of Seckler *et al.*, (1998) (see also Seckler *et al.*, Chapter 3, this volume), on the erroneous view that all water applied in irrigation is consumed (i.e. a large proportion of the flow can be reused elsewhere), a unit of efficiently used local rainwater does not necessarily mean a unit lost for downstream use. For example, many water-harvesting systems have as both a direct and indirect objective the changing of the partitioning of flow, e.g. from surface to subsurface runoff, rather than increasing consumptive use (Scott and Flores-Lopez, 2003).

This chapter presents the agrohydrological rationale to focus on WP in rain-fed agriculture, and identifies key management challenges in the attempt to upgrade rain-fed agriculture. It presents some field experiences on system options for increased WP in smallholder farming in drought-prone environments. Implications for watershed management are discussed, and the links between WP for food and securing an adequate water flow to sustain ecosystem services are briefly analysed. The focus is on semi-arid and dry subhumid tropical agroecosystems, where the increase in WP is most important. Most of the research examples are taken from sub-Saharan Africa, which faces the largest food-deficit and water-scarcity challenges today.

Rainwater Management: the Rationale

A broad approach to WP in land management that covers both irrigated and rain-fed agriculture has implications for water-resources management. Conventionally, the focus of attention regarding global, regional and national freshwater resources and withdrawals has been on the stable and accessible surface and subsurface flow of water in rivers, lakes and groundwater, the so-called blue-water branch in the hydrological cycle (UN, 1997; Cosgrove and Rijsberman, 2000). Blue water is withdrawn not only as direct blue (liquid)-water uses in households, for municipalities, livestock and industry but also as direct withdrawals for irrigated agriculture (of which the consumptive proportion eventually returns to the atmosphere as green vapour or ET flow). Regionally, there are signs of present or predicted near-future physical scarcity of 'blue'-freshwater resources. The International Water Management Institute (IWMI, 2000) estimated that by 2025 30% of the world population might live in regions subject to physical water scarcity (read 'blue'-water scarcity).

The fear of rapidly growing water-scarcity problems, especially in arid and semi-arid tropical regions of the world, is based on analyses comparing blue-water availability with actual blue-water withdrawals, and projections of future withdrawals based on general per capita water requirements. This approach has recently been criticized as it does not include the contribution of rain-fed agriculture in terms of fresh water to cover human water requirements. This has significant implications for water-resources assessments, given the important role of rain-fed food production and that 90% or 1600 m^3 per capita $year^{-1}$ of human freshwater needs are water for food (Rockström and Falkenmark, 2000; Rockström, 2001). However, conventional water-resources assessments highlight the limited possibilities of expansion of direct blue-water withdrawals. Globally, humankind withdraws approximately 4000 Gm^3 $year^{-1}$ (Shiklomanov, 2000), which is projected to reach 5250 Gm^3 $year^{-1}$ in 2025, as a result of population growth and socio-economic development. This is a serious problem in light of the global availability of blue-freshwater flow estimated at 12,500 Gm^3 $year^{-1}$ (Postel *et al.*, 1996). Furthermore, de Fraiture *et al.* (2001) considered that at least 30% of the blue-water flow must be secured as an environmental flow to avoid environmental hazards, such as salt and pollutant build-up and groundwater decline, leaving a utilizable ceiling of 8700 km^3 $year^{-1}$. The increased pressure on finite blue-freshwater resources would suggest limitations in the opportunities to expand the area under irrigation.

This brings our attention to the green-flow branch in the hydrological cycle. Of the global estimated average of 113,000 Gm^3 $year^{-1}$ of precipitation over land areas, 41,000 Gm^3 $year^{-1}$ forms the blue-runoff branch and the remaining 72,000 Gm^3 $year^{-1}$ forms the return flow of green water as ET. Green-water flow sustains rain-fed agriculture, as well as all other water-dependent ecosystems, such as forests, woodlands, grazing lands, grasslands and wetlands.

Partitioning of rainfall in rain-fed agriculture and the biophysical dynamics of green-water flow at plant and production-system level have recently been studied. However, relatively less attention (compared with irrigation efficiency) has been paid to the opportunities at hand to improve agricultural WP within the large (relative to blue-water flow) component of green-water flow in the on-farm water balance and the hydrological cycle at catchment, basin and global levels. In a first global estimate, Rockström *et al.* (1999) calculated global withdrawals of green water to sustain rain-fed agriculture at 4500 Gm^3 $year^{-1}$, compared with some 2500 Gm^3 $year^{-1}$ estimated for irrigated agriculture (Shiklomanov, 2000).

Figure 9.1 shows the geographical distribution of green (rain-fed)- and blue (irrigated)-water withdrawals to produce cereals. Data on blue-water withdrawals for irrigation, as well as data on areas under rain-fed agriculture and estimated grain yields in irrigated and rain-fed farming systems, are taken from IWMI (2000). The green-water withdrawals were calculated assuming a global water productivity in rain-fed grain production of 3000 m^3 t^{-1} grain (ET flow). As seen from Fig. 9.1, the majority of countries (79%) of the world depend predominantly on the return flow of

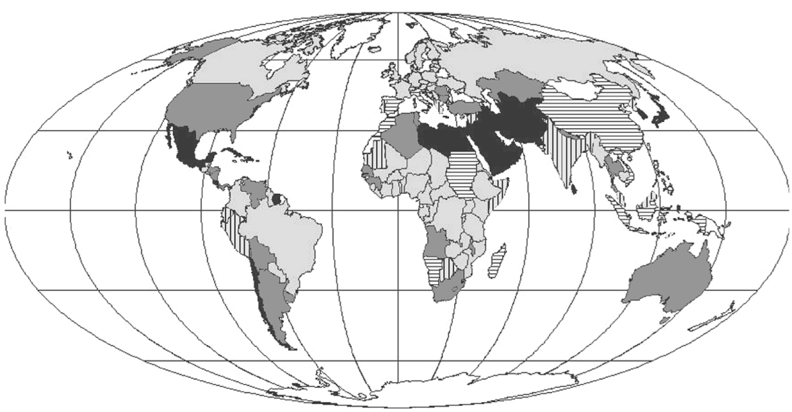

Fig. 9.1. Predominant source of water flow – green or blue – to produce cereals (grain) at country level. ☐: Countries with > 80% green-water dependence, i.e. > 80% of water used to produce cereal foods originates from rain-fed agriculture. ■: countries where 60–80% originates from green water. ■: countries with > 80% blue-water dependence, i.e. where > 80% of water withdrawals for cereal-food production originates from blue water. ▥: countries where 60−80% originates from blue water. ▤: countries with 40−60% green-water dependence. Countries where some component of source data was lacking are marked in white.

green water in rain-fed agriculture to produce cereals. Not surprisingly, the countries (predominantly in North Africa and the Middle East) that depend primarily on blue-water withdrawals for irrigated grain production correspond to the countries that, in conventional water assessment, are predicted to be facing the most severe water-scarcity problems.

Like all global assessments, the country-scale analysis gives little guidance on challenges and opportunities at the local scale. However, it suggests that there are opportunities to produce more food per drop of water if the focus is changed from the downstream blue-runoff-water resource to the upstream position, where the rainfall enters the soil–plant system. Such a shift towards rainwater management forms a rational entry point for integrated agricultural water management that encompasses both green-rain-fed withdrawals and blue-irrigation withdrawals. Moreover, the shift towards an upstream focus is crucial, especially in respect of resource-poor smallholder farmers, as it opens up the possibility of a kind of water management that will benefit from unutilized gravitational energy.

Upgrading Rain-fed Agriculture: Challenges and Opportunities

Hydroclimatic challenges

Water-related problems in rain-fed agriculture in the water-scarce tropics are often related to high-intensity rainfall with large spatial and temporal variability, rather than to low cumulative volumes of rainfall (Sivakumar and Wallace, 1991; Rockström *et al.*, 1998; Mahoo *et al.*, 1999). Coefficients of variation range from 20 to 40%, increasing as seasonal rainfall averages decrease. The overall result of unpredictable spatial and temporal rainfall patterns indicates a very high risk for meteorological droughts and intraseasonal dry spells. The annual (seasonal) variation in rainfall can typically range from a low of one-third of the long-term average to a high of approximately double the average, meaning that a high-rainfall year can have some six times higher rainfall than a dry year. Generally, the hydroclimatic focus in semi-arid and dry subhumid tropics is on the occurrence of meteorological droughts. Their impact on rain-fed agriculture is complete crop failure, which statistically, for semi-arid lands, occurs about once every 10 years (Stewart, 1988).

Research from several semi-arid tropical regions show that the occurrence of dry spells, i.e. short periods of 2–4 weeks with no rainfall, by far exceeds that of droughts. Stewart (1988), based on research in East Africa, indicated that severe yield reductions due to dry spells occur once or twice in 5 years, and Sivakumar (1992) showed that the frequency of seasonal dry spells lasting 10–15 days was independent of long-term seasonal averages, which range from 200 to 1200 mm in West Africa. Barron *et al.* (2003), studying the frequency of dry spells in semi-arid locations in Kenya and Tanzania, showed a minimum probability (based on statistical rainfall analysis) of 0.2–0.3 for a dry spell lasting more than 10 days at any time of the growing season of a crop, and a probability of 0.7 for such a dry spell to occur during the sensitive flowering stage (maize).

Figure 9.2 shows the probability of dry-spell occurrences based on 21 years of rainfall data (1977–1998) for a site in the semi-arid Machakos district in Kenya. Rainfall is bimodal, with the onset of the long rains in mid-March (day number 75 in Fig. 9.2) and the onset of the short rains in mid-October (day number 288 in Fig. 9.2). The average planting date occurs within the onset windows in Fig. 9.2: on day number 86 (26 March) for the long rains and on day number 304 (30 October) during the short rains. Dry-spell occurrence was also analysed for the same locations, based on water-balance modelling, to assess actual crop water availability. It showed that the maize crop experienced a dry spell exceeding 10 days during 67–80% of the rainy seasons (1977–1998) on a clay soil and during 90–100% of the rainy seasons for a sandy soil.

Obviously, mitigation of intraseasonal dry spells is a key to improving WP in rain-fed agriculture in semi-arid and dry subhumid tropical environments. There are three major avenues to achieve this:

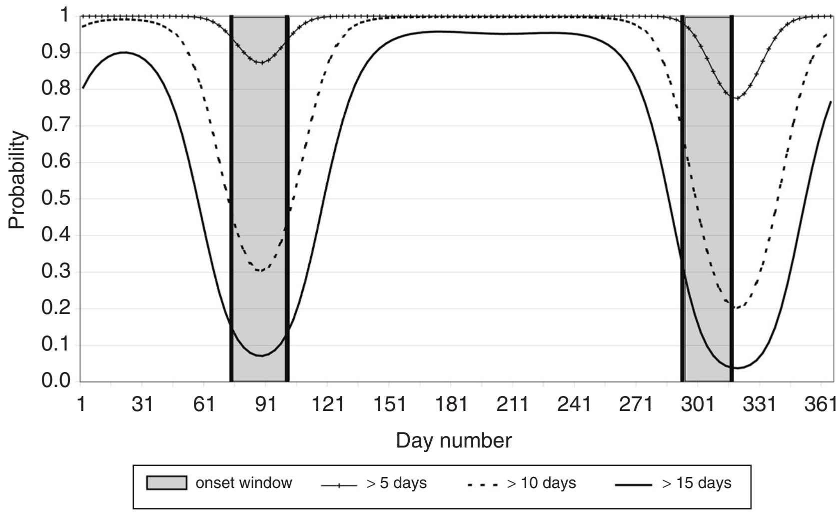

Fig. 9.2. Probability of dry spell exceeding 5, 10 or 15 days. The analysis is based on rainfall data for the period 1977−1998 at Chief Mbiuni Camp, Machakos district, Kenya. Window of planting date for long rains was from day numbers 72 to 100 (12/3 to 11/4) and similarly for short rains from day numbers 291 to 317 (17/10 to 12/11).

- Maximize plant water availability (maximize infiltration of rainfall, minimize unproductive water losses (evaporation), increase soil water-holding capacity and maximize root depth).
- Maximize water-uptake capacity of plants (timeliness of operations, crop management and soil-fertility management).
- Dry-spell mitigation using supplemental irrigation.

Hydroclimatic opportunities

The on-farm water balance can also be analysed for opportunities to improve WP. Despite a general gap in detailed knowledge on rainfall partitioning in rain-fed tropical agriculture, there are several examples of local research, often focusing on specific flow parameters (Sivakumar *et al.*, 1991; Goutorbe *et al.*, 1997; Stephens *et al.*, 1999). Figure 9.3 gives a synthesized overview of the partitioning of rainfall in semi-arid rain-fed agriculture, based on research experiences in sub-Saharan Africa. Soil evaporation generally accounts for 30–50% of rainfall (Cooper *et al.*, 1987; Wallace, 1991), a value that can exceed 50% in sparsely cropped farming systems in semi-arid regions (Allen, 1990). Surface runoff is often reported to account for 10–25% of rainfall (Penning de Vries and Djitèye, 1991; Casenave and Valentin, 1992). Large and intensive rainfall events falling on soils with low water-holding capacities result in significant drainage, amounting to some 10–30% of a rainfall (Klaij and Vachaud, 1992). The result is that productive green-water flow as T is in general reported to account for merely 15–30% of rainfall (J.S. Wallace, Institute of Hydrology, Wallingford, UK, personal communication).

Between 70 and 85% of rainfall can be considered 'lost' to the cropping system as non-productive green-water flow (as soil evaporation) and as blue-water flow (deep percolation and surface runoff). Figure 9.3 thus indicates that there is a high seasonal risk of soil-water scarcity in crop production, in addition to spatial and temporal rainfall variability.

In terms of WP can crop yields in rain-fed agriculture be increased? Rockström and Falkenmark (2000) developed an analytical tool to assess the options available to improve crop yields in semi-arid tropics from a hydrological perspective. In Fig. 9.4, the case of maize cultivated in a semi-arid tropical savan-

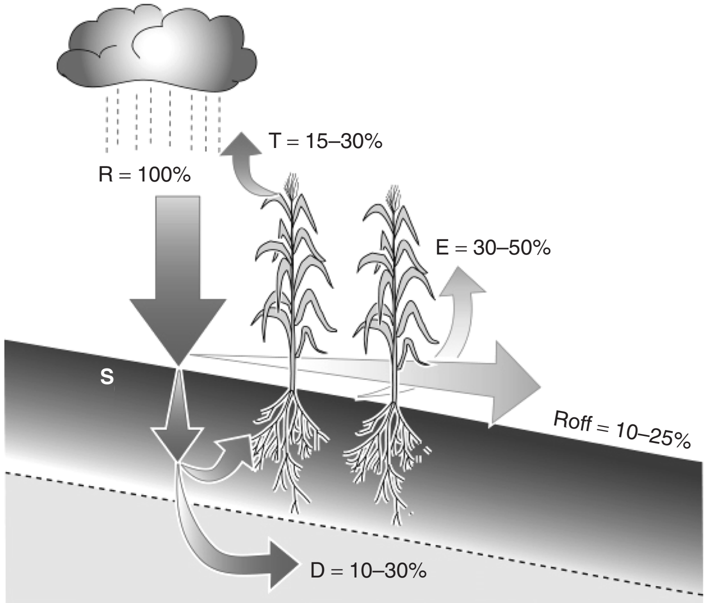

Fig. 9.3. General overview of rainfall partitioning in farming systems in the semi-arid tropics of sub-Saharan Africa. S, soil; R, rainfall; T, transpiration; E, evaporation; Roff, runoff; D, drainage.

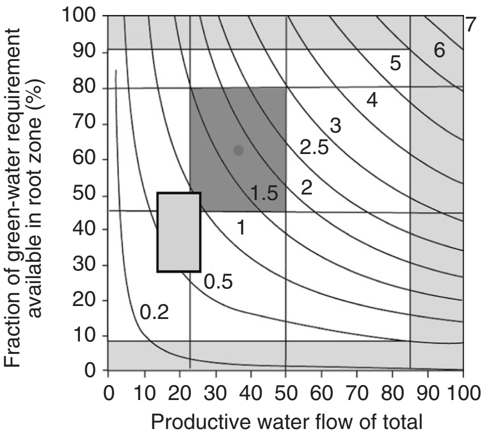

Fig. 9.4. Analysis of the effects of rainfall partitioning and plant water-uptake capacity on maize grain yields under semi-arid conditions. The larger shaded area shows the range of yields experienced on average in sub-Saharan Africa, using the rainfall partitioning range in Fig. 9.3. The smaller shaded area shows the yield range on farmers' degraded fields (Rockström and Falkenmark, 2000).

nah is presented (growing period of 120 days, daily PET = 8 mm day^{-1}, seasonal rainfall = 550 mm). Transpiration water productivity (WP_T) (kg ha^{-1} mm^{-1}) was set at 12.5 kg ha^{-1} mm^{-1} (Falkenmark and Rockström, 1993). The x axis in Fig. 9.4 shows the ratio (%) of productive green water to total green water (ratio of T to ET flow), and is an indicator of the impact of crop management on grain yield (soil fertility, crop species, timing of operations, pest management). The y axis shows the percentage of crop water requirement (CWR) available in the root zone, and is an indicator of the impact of land management on crop yields (basically the percentage of rainfall that infiltrates into the soil and is accessible to the crop).

The concave lines are isolines of equal grain yield (t ha^{-1}), with the lowest-yield line in the lower left corner and the maximum-yield isolines in the upper right-hand corner. The grey border area shows the upper boundary conditions of the model. The attainable yield level in this semi-arid case amounts to 5 t ha^{-1} grain yield. Actual observed yield levels, based on the rainfall partitioning data in Fig. 9.3, are shown by the large square. Poor rainfall partitioning (a vertical drop along the y axis) reduces the possible yields with 1–2.5 t ha^{-1} and poor plant water-uptake capacity reduces yields with 1.5–3 t ha^{-1}. The average actual yield level ranges from 1.5 to 2 t ha^{-1}. The common on-farm reality is shown by the smaller square, with an actual yield range of 0.5–1 t ha^{-1}. In the on-farm case, only 35–55% of the CWR is available in the root zone (due to high runoff, a weak root system and deep percolation) and productive green water amounts to only 15–25% of the total green-water flow (indicating large evaporation losses).

The analysis suggests a large scope for improving yield levels within the available water balance in rain-fed farming systems. It seems that there are no agrohydrological limitations to enabling even a large and stable yield increase from, for example, 0.5 t ha^{-1} to 2 t ha^{-1} (i.e. a quadrupling of yields) in semi-arid environments. The challenges are to maximize infiltration (move up along the y axis), to mitigate dry spells (increase the amount of water available in relation to CWR over time) and to improve, primarily, soil-fertility management in order to increase the productive green-water ratio (push the system to the right along the x axis).

A note on water productivity

The focus in this chapter is to improve system WP by reducing losses in the on-farm water balance in favour of productive T flow. This is in line with Gregory (1989), who suggested that, because runoff, deep percolation and evaporation can constitute large flows in the water balance, water-use efficiency in semi-arid tropics should be studied in terms of yield per unit rainfall, whereby consideration is given to the impact of management on all water flows. Rainfall water productivity (WP_R) represents a valuable parameter for assessing productivity in semi-arid tropical farming systems (Bennie and Hensley, 2001) as it indicates the extent by which green- and blue-water losses are minimized in favour of productive T flow. Also, management can easily improve WP_R. In contrast, WP_T, which is essentially affected by the atmospheric demand for water and the photosynthetic pathway, i.e. directly linked to the characteristics of the crop species, is relatively difficult to influence within a given cropping system (Sinclair *et al.*, 1984). Instead, from a green-water perspective, WP can more easily be improved by increasing the ratio of evaporation losses from the crop to the evaporation losses from the soil (E_c/E_s). Another option is to convert soil evaporation to plant T, i.e. by increasing yield per unit ET (WP_{ET}).

Water Productivity: System Opportunities

Supplemental irrigation for dry-spell mitigation

An interesting option to increase WP at production-system level is to bridge dry spells through supplemental irrigation of rain-fed crops (Oweis *et al.*, 1999; SIWI, 2001). Supplemental irrigation in smallholder farming systems can be achieved with water-harvesting systems that collect local surface runoff (sheet, rill and gully flow) in small storage structures (100–1000 m^3). Water harvesting, broadly defined as the concentration of surface runoff for productive purposes, has ancient roots and still forms an integral part of many farming systems worldwide (Evanari *et al.*, 1971; Agarwal and Narain, 1997). However, *in situ* systems that aim at water conservation (i.e. maximizing soil infiltration and water-holding capacity) dominate, while storage systems for supplemental irrigation are less common, especially in sub-Saharan Africa (SIWI, 2001).

On-farm research in semi-arid locations in Kenya (Machakos district) and Burkina Faso (Ouagouya) during 1998–2000 indicates a significant scope for improving WP in rain-fed farming through supplemental irrigation, especially if combined with soil-fertility management (Barron *et al.*, 1999; Fox and Rockström, 1999). Surface runoff from small catchments (1–2 ha) was harvested and stored in manually dug farm ponds (100–250 m^3 storage capacity). Simple gravity-fed furrow irrigation was used. During the experimental phase (1998–2000), covering three rainy seasons in Burkina Faso (monomodal rain pattern) and five in Kenya (bimodal rain pattern), supplemental irrigation amounted, on average, to 70 mm per growing season, with a range of 20–220 mm. Seasonal rainfall ranged from 196 to 557 mm in Kenya and from 418 to 667 mm in Burkina Faso. In Kenya, one rainy season was classified as a meteorological drought (short rains of 1998/99), resulting in complete crop failure. One season at each site (long rains 2000 in Kenya and the rainy season 2000 in Burkina Faso) resulted in complete crop failure for most neighbouring farmers, while the water-harvesting system enabled a harvest of an above-average yield (> 1 t ha^{-1}). The seasonal long-term average yield in both areas is approximately 0.5 t ha^{-1}. Grain yields and rain-use efficiencies (kg dry-matter grain per mm rainfall) for the studied water-harvesting system are shown for sorghum in Burkina Faso (Fig. 9.5a) and for maize in Kenya (Fig. 9.5b). Each point represents an average combination of five replicates of water harvesting/fertilizer application for any rainy season. In Burkina Faso, on shallow soil with

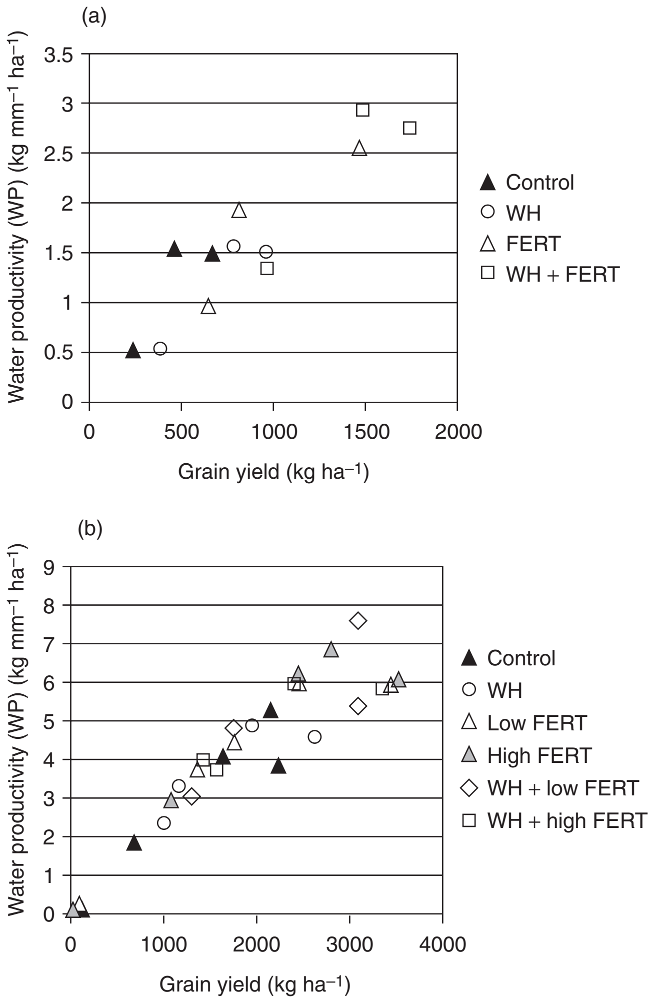

Fig. 9.5. System water productivity (WP) (kg grain per unit rainfall + supplemental irrigation) for sorghum in Burkina Faso (a) and for maize in Kenya (b). Control, traditional farmers' practice with no fertilizer application; WH, supplemental irrigation using water harvesting; FERT, fertilizer application (30 kg ha^{-1} N in Burkina Faso, and two levels in Kenya with low 30 kg N ha^{-1} and high 80 kg N ha^{-1}).

low water-holding capacity, supplemental irrigation alone improved water-use efficiency (rainfall + irrigation) by 37% on average (from 0.9 to 1.2 kg ha^{-1} mm^{-1}) compared with the control (traditional rain-fed practice with manure but no fertilizer). The corresponding ratio for the Kenyan case, on deep soil with high water-holding capacity, was 38% (from 2.2 to 3.1 kg ha^{-1} mm^{-1}).

The largest improvement in yield and WP_R was achieved by a combination of supplemental irrigation and fertilizer application. Interestingly, for both locations, fertilizer application alone (in Kenya with low application of 30 kg N ha^{-1} and high application of 80 kg N ha^{-1}) resulted in a higher average yield and WP_R than supplemental irrigation alone during years with gentle dry spells. For seasons with severe dry spells, e.g. long rains of 2000 in Kenya, non-irrigated crops failed completely, independent of fertilizer level. Nevertheless, the field data indicate that full benefits of water harvesting for supplemental irrigation can only be met by simultaneously addressing soil-fertility management.

An interesting aspect of the observed WP improvements is that WP increases in pace with yield. Assuming a linear relationship between crop yield and T (which is generally the case for a given system), then the WP increase with yield in Figs 9.5a and 9.5b originates from 'crop per drop' improvements as a result of reduction in water losses (evaporation, drainage and runoff). Similar findings of a win–win relationship between WP and yield increase are found by analysing the data of Pandey *et al.* (2000) on maize in the Sahel and of Zhang and Oweis (1999) for wheat in the Mediterranean region. However, the water-use and yield results of Norwood (2000) for limited irrigation of dryland maize do not suggest a linear relation between WP_R and grain yield. The conditions under which WP improvements are achieved as a result of system improvements need further investigation.

The relative contribution to system productivity of supplemental irrigation is assessed by calculating the incremental WP for supplementally irrigated treatments (kg additional grain produced per mm of supplemental irrigation). As seen in Table 9.1 the incremental WP is substantially higher than the seasonal WP (ranging from 2.5 to 7.6 kg ha^{-1} mm^{-1} compared with an overall WP of 0.9–1.2 kg ha^{-1} mm^{-1}). The situation is more complex on soil with greater water-holding capacity and therefore better able to cope with dry spells, as illustrated by the Kenyan case (Table 9.2). Incremental WP improvements are only achieved during rainy seasons with severe dry spells, while during rainy seasons with adequate rain of good distribution (short rains 1999/2000 and 2000/01) the incremental value can be negative.

Table 9.1. Incremental water productivity of supplemental irrigation (Burkina Faso).

Fertilizer application	1998 (kg ha^{-1} mm^{-1})	1999 (kg ha^{-1} mm^{-1})	2000 (kg ha^{-1} mm^{-1})
Non-fertilized	4.9	2.5	3.6
Fertilized	4.6	5.4	7.6

Table 9.2. Incremental water productivity of supplemental irrigation (Kenya).

Fertilizer application	SR 1998/99 (kg ha^{-1} mm^{-1})	LR 1999 (kg ha^{-1} mm^{-1})	SR 1999/2000 (kg ha^{-1} mm^{-1})	LR 2000 (kg ha^{-1} mm^{-1})	SR 2000/01 (kg ha^{-1} mm^{-1})
0 F	6.0	6.3	−9.3	4.2	19.9
30 F	3.5	4.8	32.7	5.5	−17.2
80 F	2.8	4.4	−19.1	7.0	−8.1

Water harvesting for microirrigation

For resource-poor smallholder farmers in water-scarce areas, even small volumes of stored water for supplemental irrigation can significantly improve the household economy. In the Gansu Province in China, small 10–60 m^3 (on average 30 m^3) subsurface storage tanks are promoted on a large scale. These tanks collect surface runoff from small, often treated, catchments (e.g. with asphalt or concrete). Research using these subsurface tanks for supplemental irrigation of wheat in several counties in the Gansu Province (Li *et al.*, 2000) indicates a 20% increase in WP (rain amounting to 420 mm + supplemental irrigation ranging from 35 to 105 mm). WP increased, on average, from 8.7 kg ha^{-1} mm^{-1} for rain-fed wheat to 10.3 kg ha^{-1} mm^{-1} for wheat receiving supplemental irrigation. Incremental WP ranged from 17 to 30 kg ha^{-1} mm^{-1}, indicating the large relative added value of supplemental irrigation. Similar results were observed on maize, with yield increases of 20–88% and incremental WP ranging from 15 to 62 kg ha^{-1} mm^{-1} of supplemental irrigation (Li *et al.*, 2000).

The irrigable land from these subsurface tanks is limited to 400–800 m^2. In many farming communities the tanks are probably only of interest for irrigation of high-value cash crops. A survey in Kenya among smallholder farmers, shows that farmers would rarely consider supplemental irrigation of food crops and would rather use stored water to irrigate cash crops (Jurdell and Svensson, 1998). Inspired by the Chinese subsurface tanks, similar systems are at present being developed and promoted in Kenya and Ethiopia (G. Shone, RELMA/Sida, Nairobi, Kenya, personal communication). In Kenya (Machakos district) these tanks are used to irrigate kitchen gardens, and they enable farmers to diversify sources of income from the land. The microirrigation schemes are promoted together with commercially available low-pressure drip-irrigation systems. Cheap drip kits (e.g. the Chapin bucket kit) save water and labour and are increasingly being adopted by farmers in, for example, Kenya. Combining water harvesting with drip irrigation can result in very significant WP improvements (Ngigi *et al.*, 2000).

Conservation tillage

There is ample evidence indicating that the conventional farming system in the tropics, based on soil inversion using plough and hoe, contributes to soil erosion and soil desiccation. Plough pans impede soil infiltration and root penetration, and frequent soil inversion results in accelerated oxidation of organic matter and soil erosion by wind and rain (Benites *et al.*, 1998). Conservation tillage (CT) covers a spectrum of non-inversion practices from zero-tillage to reduced tillage; it aims to maximize soil infiltration and soil productivity and minimize water losses, while conserving energy and labour. Although CT is not a new concept, the relatively recent successes, e.g. in Brazil (Derpsch, 1998), have inspired research and development efforts in sub-Saharan Africa and Asia. Examples of successful CT systems, where crop yields have been significantly increased, soil erosion reduced and conservation of water improved, can be found in several countries in sub-Saharan Africa, e.g. Ghana, Nigeria, Zimbabwe, Tanzania, South Africa and Zambia (Elwell, 1993; Oldreive, 1993). However, these successes are mostly confined to commercial farmers.

CT has several attractive effects on WP. Traditionally, conservation in agriculture has focused on soil conservation (even though labelled soil and water conservation), with the aim of reducing soil erosion. Even success stories, like the *Fanya juu* terracing in the Machakos district, Kenya (Tiffen *et al.*, 1994), show little or no evidence of actual improvements of WP in agriculture. The recently raised questions of 'what to do between the terraces' in order to increase crop yields and 'how to increase crop per drop of rain' have shifted the focus towards CT, which also enables improved timing of operations, which is crucial in semi-arid rain-fed farming and which has (compared, for example, with storage-water harvesting) the attraction of being applicable on most farmlands.

Table 9.3. Rainwater productivity (kg ha^{-1} mm^{-1}) showing variation (SD) and statistical T-test analyses (comparing CT practices with conventional ploughing with or without fertilizer application).

Treatment	WP_R (kg ha^{-1} mm^{-1})	SD	Comparative analysis: C − FERT Statistical significance[a]	Multiplier	C + FERT Statistical significance[a]	Multiplier
Ripper	10.1	4.9	***	2.8	*	1.4
Ripper + CC	10.6	5.8	***	2.9	**	1.5
Ripper − FERT	8.4	3.7	***	2.4	NS	1.2
Pitting	8.2	4.1	***	2.3	*	1.2
C + FERT	7.0	4.4	***	2.0		
C − FERT	3.6	2.2				

[a]Statistical significance at the 0.001 (***), 0.01 (**) and 0.05 (*) levels of probability.
NS, not significant; Ripper, Magoye ripper; Ripper + CC, Magoye ripper + cover crop (Dolichos lablab); Ripper − FERT, Magoye ripper without fertilizer application; C + FERT, conventional mouldboard plough with fertilizer application; C − FERT, ploughing without fertilizer application.

There are several examples of WP improvements using CT in rain-fed farming. Zero-tillage research using planting drills on wheat in Pakistan show water savings of 15–20% (on average, an estimated 100 mm ha^{-1}) through reduced evaporation, runoff and deep percolation, while increasing yields and saving on fuel (Hobbs *et al.*, 2000).

Over the last decade, promotion of animal- and tractor-drawn CT using rippers and subsoilers among smallholder farmers in the semi-arid Babati district, Tanzania, has resulted in significant WP increases. As seen from Fig. 9.6, the WP of rain was estimated at approximately 1.5 kg ha^{-1} mm^{-1} in the mid-1980s under conventional disc-plough agriculture, compared with a progressively increasing trend from 2 to 4 kg ha^{-1} mm^{-1} during the 1990s after the introduction of mechanized subsoiling (Rockström and Jonsson, 1999).

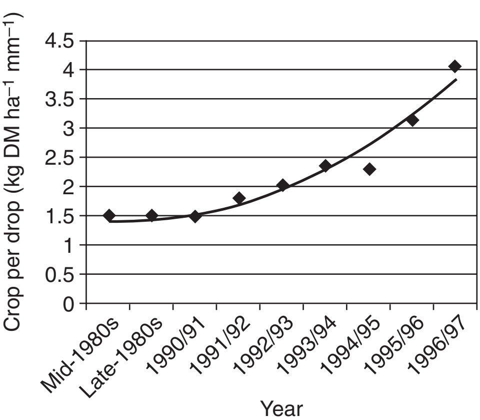

Fig. 9.6. Development of WP of rain (kg DM grain ha^{-1} mm^{-1}) of maize in the Babati district, Tanzania, before the introduction of conservation tillage (mid-1980s to 1990/91) compared with after introduction of conservation tillage (1991/92 onwards). DM, dry matter.

On-farm trials on animal-drawn and manually based CT systems (Magoye ripper and Palabana subsoiler from Zambia developed by IMAG-DLO) in Arusha and Arumeru districts, Tanzania, show similar improvements in WP: WP_R increased when shifting from a mouldboard-plough-based system (C = control) to various CT practices (Table 9.3). The data originate from 2 years (long rains, 1999 and 2000) with six to eight farmers and two replicates per farm. The improved WP is attributed primarily to improved timing of planting, root penetration and soil infiltration.

Watershed management

Upgrading rain-fed agriculture in semi-arid tropical environments will require planning of land management at the watershed scale, rather than having the conventional focus on farm or field level. A shift is needed from the 'soil conservation' approach, where surface runoff entering a farm is seen as a threat to be disposed of (e.g. with graded cut-off drains), to a 'productivity' approach, where surface runoff generated in one part of a watershed is collected and used as a resource for both agricultural and domestic purposes. Such planning is complex among smallholder farmers, since even a small runoff-collecting system will involve multiple landowners. At present, there is little or no attention given to ownership of locally produced surface runoff, but one may expect this to become an issue of importance if runoff is to be successfully managed on a larger scale for local production purposes. That this scenario is not just hypothetical is shown by a recent example from India. Small-scale farmers in the region of Rajastan installed a water-harvesting structure for water retention (a so-called *Johad*) as a strategy to reduce the degradation and livelihood deterioration caused by 3 consecutive years of drought. The Rajastan irrigation district, fearing that the water-harvesting structure would threaten water supply to a dam located downstream, judged the structure illegal (as all rain in the basin is under the authority of the Irrigation Department) and ordered (June 2001) the immediate destruction of the structure (*Down to Earth*, 2001). Many countries lack policies and legislation to manage local initiatives of rainwater management, especially for agricultural purposes (Hartung and Patschull, 2001).

As shown by several hydrological studies at watershed and basin scale, upstream shifts in water-flow partitioning may result in complex and unexpected downstream effects, both negative and positive, in terms of quantity and quality of water (Vertessy *et al.*, 1996). In general, though, increasing the residence time of runoff flow in a watershed, e.g. through practices such as water harvesting and CT, may have positive environmental, as well as hydrological, implications downstream. The hydrological implications at watershed and river-basin level of scaling up system innovations, such as water harvesting, are still unknown and require further research.

System Implications: Balancing Water for Food and Nature

It is estimated that most of the global green-water flow (88%) is at present used to sustain biomass growth in the world's biomes (Rockström *et al.*, 1999). While agriculture (rain-fed and irrigated) accounts for an estimated 7000 Gm^3 $year^{-1}$, forests and woodlands require an estimated average green-water flow of 40,000 Gm^3 $year^{-1}$, grasslands an estimated 15,100 Gm^3 $year^{-1}$ and wetlands an estimated 1100 Gm^3 $year^{-1}$. A doubling of food production over the next 25 years would (without considering WP increases) result in roughly a doubling of water utilization in agriculture. Increased withdrawals of water in rain-fed and irrigated agriculture may have negative implications for water availability to sustain direct human withdrawals and indirect withdrawals to sustain ecosystem services. The expected shifts in water flows in the water balance would affect both nature and economic sectors depending on direct water withdrawals. As suggested in this chapter, a promising avenue for upgrading rain-fed agriculture is through water harvesting, which enables mitigation of dry spells. Such measures would involve the addition of a blue-water component, through storage of surface or subsurface runoff, to the rain-fed system, i.e. developing rain-fed farming into a mixed system with an irrigation component. Carried out on a large scale (e.g. at basin level), water-harvesting promotion may have an impact on downstream blue-water availability. These effects are bound to be site-specific and need to be studied further. However, it is not certain that an increase in ET in rain-fed agriculture upstream automatically results in reduced water availability downstream. Surface runoff generated at the farm level may be lost during its journey through the catchment as evaporation or as blue water of limited use in saline rivers, before reaching a stable surface or subsurface freshwater source. Furthermore, there are large variations in green-water-flow estimates in agriculture, as both rainfall and green-water flow exhibit large spatial and temporal variability. On average, grain crop WP (WP_{ET}) ranges between 3.5 and 10 kg ha^{-1} mm^{-1} (1000–3000 m^3 t^{-1}) for tropical grains. However, as WP_{ET} is affected by biophysical factors as well as management, the actual range is much wider, with WP_{ET} values as low as 1.5 kg ha^{-1} mm^{-1} (6000–7000 m^3 t^{-1}) for degraded and poorly managed systems not being uncommon in rain-fed drylands (Rockström *et al.*, 1998).

Conclusions and Discussion

There is no doubt that the immense challenge of doubling food production over the next 25 years in order to keep pace with population growth requires focus on WP in both rain-fed and irrigated agriculture. As shown in this chapter, even in water-scarce tropical agroecosystems, there appear to be no hydrological limitations to doubling or, in many instances, even quadrupling yields of staple food crops in rain-fed smallholder agriculture. Furthermore, evidence suggests that there are several appropriate technologies and methodologies to hand to enable development towards improved soil productivity and WP. In a broad overview of recent projects regarding sustainable agricultural practices and technologies in 52 countries, Pretty and Hine (2001) showed that yield increases as a result of introducing practices such as water-harvesting, CT and drip irrigation amounted to 50–100% on average (with examples of up to 700% increases). The challenge, as pointed out by Pretty and Hine (2001), is to learn from these examples and establish policies that enable their proliferation.

Interestingly, even when focusing on WP in semi-arid rain-fed farming systems, where water is considered a major limiting factor for crop growth, factors other than water are shown to be at least as (if not even more) critical for productivity improvements. The experience with water harvesting for supplemental irrigation in Burkina Faso and Kenya clearly shows that soil-fertility management plays as important a role as water management. In both cases, fertilizer application alone resulted, on average, in higher WP and yields than supplemental irrigation alone. Similarly, for *in situ* water harvesting using CT in Tanzania, water conservation on its own (e.g. ripping and subsoiling) resulted in yields and WP similar to those obtained with improved soil fertility alone in conventionally ploughed systems. However, the water-harvesting studies in Burkina Faso showed that integrated soil-nutrient and water management increased yields threefold, compared with a yield increase of 1.5–2 times over traditional yield levels when either water conservation or better soil fertility was introduced.

Despite these biophysical facts, farmers' investment decisions are strongly influenced by their risk perceptions. Risk of reduced or no return on invested capital in rain-fed semi-arid farming is directly related to the unreliable rainfall distribution. Therefore, as long as farmers 'live at the mercy of rainfall', one should not be surprised at the extremely low level of investments in fertilizers (less than 20 kg ha^{-1} year^{-1} in sub-Saharan Africa), in improved crop varieties and in pest management. To manage water, especially by providing farmers with the means to bridge recurrent dry spells, e.g. through small-scale water harvesting, may be the most sustainable entry point for the improvement of farming systems in general. This form of upgraded rain-fed farming may stimulate further capital and time investment in smallholder rain-fed farming. All evidence suggests that if only crop water access is secured, investments in soil fertility, crop and timing of operations will pay off in terms of substantially increased soil productivity and WP.

This chapter has not considered the social and economic viability of water-harvesting structures for supplemental irrigation among resource-poor farmers. Tentative assessments of manually dug farm ponds and subsurface tanks indicate that the economic viability depends to a large extent on the opportunity cost of labour. With low-value labour (which is often the case during dry seasons in remote rural areas) and considering the dramatic difference a water-harvesting/storage system can play during years of severe dry spells (the difference between total crop failure and having a crop), it is likely that the investment can be readily afforded and quickly recovered. However, there is a need for more detailed studies, which take into account the local environmental, institutional and socio-economic conditions.

The most interesting opportunities for upgrading smallholder rain-fed agriculture may be found in the realm of sectoral and economic system integration and diversification. Reduced risk of crop failures through supplemental irrigation implies the development of a mixed farming system with components of both rain-fed and irrigated agriculture. The time may be ripe for abandoning the sectoral distinction between irrigated and rain-fed agriculture. The implications of such a reform would be substantial. Professionally, there is still a divide between irrigation engineers dealing with irrigation management and agronomists focusing on rain-fed agriculture. Irrigation and rain-fed agriculture generally fall under different ministries (irrigation under 'blue'-water resources ministries and rain-fed agriculture under 'green' ministries of agriculture, natural resources or environment). Integrating the two may result in interesting management and technological advances in the grey zone between the purely blue and purely green food-producing sectors.

Blended upgrading also opens the door to the diversification of farming systems. A smallholder farmer's investment in supplemental irrigation will be an entrepreneurial business step, which will most probably result in a broadened basket of crops produced at farm level. This will reduce farmers' vulnerability to external climatic factors, but will also put increased pressure on the need for functioning markets and infrastructure. Diversification in favour of cash crops with a relatively lower proportion of staple food crops can have interesting virtual water implications. A shift from a staple food crop to a cash crop with similar WP but with a different market value can give rise to virtual water gains. If the same amount of water can be used to generate a higher market price, then the economic gain can be used to buy food grain. This implies a flow of virtual water from regions with a relatively greater (hydrological) comparative advantage for the production of staple foods. In summary, in spite of the wide range of complex biophysical and socio-economic factors affecting WP in rain-fed farming systems in dry subhumid to semi-arid tropics, reducing the risk of crop failure due to water stress may provide the trigger for a much-needed positive spiral of agricultural development in the smallholder sector.

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