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A conceptual framework for the improvement of crop water productivity at different spatial scales

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Abstract

Total food crop production still needs to increase to feed a growing world population, and this increase needs to be accomplished under increasing scarcity of water. This challenge has lead to the notion that crop water productivity (WP) needs to be increased. The debate on how to increase WP is confounded by different definitions and scale levels of analysis. Moreover, improvements in WP do not necessarily mean the production of more food. A systematic framework built on generic principles for the analysis of WP can help to identify interventions that can contribute to the dual goal of increasing food production and saving water. In this paper, a conceptual framework with four principles is proposed that can be applied at different scales: (1) increase transpirational crop water productivity, (2) increase the storage size for water in time or space, (3) increase the proportion of non-irrigation water inflows to the storage pool, and (4) decrease the non-transpirational water outflows of the storage pool. These principles can be applied to the improvement of genetic resources and to the improvement of natural resource management. The framework is illustrated with examples at the plant, field and (small) agricultural landscape level, for cropping systems found in semi-arid areas to flooded rice in monsoon climates.

Keywords: Crop production; Water productivity; Water saving; Systems analysis

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1. Introduction

Global agriculture in the 21st century faces two major challenges. Total food production needs to increase to feed a still growing world population, and this increase needs to be accomplished under increasing scarcity of water resources. Falkenmark and Rockström (2004) estimated that, to adequately feed 9.3 billion people in 2050, consumptive water use (i.e., transpired water) by all food and fodder crops needs to increase from its present estimated level of 7000 km^3 $year^{-1}$ to 12,586 km^3 $year^{-1}$. However, fresh water resources are increasingly getting scarce because of increased competition among a multitude of users (Pimentel et al., 2004; Rijsberman, 2006).

The challenge to produce more food under increasing water scarcity has lead to the notion that crop water productivity (WP) needs to increase (see Kijne et al., 2002, 2003, for recent overviews). However, the debate on how to increase WP is confounded by different definitions and scale levels of analysis. At the crop level, WP can be defined as the ratio of biomass with economic value (for example grain yield of cereals) over amount of water transpired (WP_T). Since transpiration is the only water flow in a field actually passing through the crop, this water productivity can be labeled as "productive". Transpiration depletes the available stock of water since it is no longer available for reuse. Another water flow that depletes the stock of water is evaporation, which is often taken together with transpiration in the term evapotranspiration. The WP_{ET} can de defined as the ratio of economic biomass over amount of water evapotranspired. Quite often, however, the distinction between WP_{ET} and WP_T is not clearly made (e.g., Bessembinder et al., 2003). Increasing WP_{ET} can be accomplished by decreasing the amount of evaporation, which, however, does not affect WP_T. On the other hand, if an increase in WP_{ET} is realized through an increase in yield, then the WP_T may increase as well. Since, in most practical field conditions evapotranspiration is hardly measured, a pragmatic way to look at WP is through water inflows rather than through water outflows. The WP_{IR} can be defined as the ratio of economic biomass over total amount of water received by irrigation and rainfall. Improvements in WP_{IR} can be realized by reducing non-productive outflows of the field, such as seepage and percolation, so that less irrigation is required (e.g., Belder et al., 2005; Bouman et al., 2005). However, measures that reduce seepage and percolation do not affect WP_T or WP_{ET}. Moreover, an increase in WP_{IR} can be associated with a decrease in yield when combined irrigation and rain inputs drop well below evapotranspiration requirements so that total crop production is threatened (Bouman and Tuong, 2001). Finally, water savings at the field level do not always translate into water savings at the regional level (Molden et al., 2003; Seckler, 1996). For example in irrigated rice production, most water-saving technologies increase WP_{IR} and save water through a reduction in seepage and percolation flows (Tuong et al., 2005). Both flows, however, could be recaptured and reused further downstream so that field-level water-savings and WP_{IR} values can not simply be aggregated into regional values (Loeve et al., 2004a).

Merely "increasing water productivity" may not solve the dual challenge of increasing food production and saving water. Nor is it easy to compare or extrapolate empirical findings from one site or one scale level to another if the underlying mechanisms of increased WP are not understood. A systematic framework built on generic principles for the analysis of WP can help in identifying interventions to increase food production while saving water. These interventions can be improvement of genetic resources (germplasm) or of natural resource management. In this paper, a conceptual framework is formulated that can be applied at different spatial scales. The framework is illustrated for the plant, field and (small) agricultural landscape level.

2. Conceptual framework

The overarching goals to increase food production and save water resources can be formulated as two simple objectives:

- Increase total crop production.
- Decrease use of scarce or expensive irrigation water.

In conventional terms, total crop production is the land productivity (yield) times the area of land used. Analogously, we can calculate production as the water productivity times the amount of water used:

$$Y = \mathrm{WP_T} \times T, \tag{1.1}$$

where

- Y = amount of produce (kg),
- $\mathrm{WP_T}$ = crop produce per unit water transpired (kg produce $\mathrm{kg^{-1}}$ water),
- T = amount of transpired water by the crop (kg).

Rearranging formulation (1.1), water productivity can be written as

$$\mathrm{WP_T} = Y/T. \tag{1.2}$$

Produce is the product of the harvest index and total above-ground biomass:

$$\mathrm{WP_T} = \mathrm{HI} \times B/T, \tag{1.3}$$

where

- HI = harvest index of the crop (kg $\mathrm{kg^{-1}}$),
- B = biomass of the crop (kg).

The fraction B/T is also known to physiologists as transpiration efficiency. The harvest index is the proportion of produce with economic value over total biomass, and can have any value between 0 and 1. Some crops have more than one useful produce, such as cereals that can produce both grains for human consumption and straw for cattle feed, and the HI can be a weighted index of the different products.

Considering formulations (1.1)–(1.3), we arrive at the three "identities" proposed by Passioura (1977) to increase total grain yield under drought: increase transpiration efficiency, increase harvest index or increase the total amount of water transpired.

Transpiration is the amount of water withdrawn from a certain storage pool, which can be characterized by its water balance:

$$\delta W = \text{Inflow} - T - \text{Other outflow}(\text{kg}), \qquad (2.1)$$

where

- δW = change in stored water (kg),
- Inflow = sum of all water inflow components (kg),
- Other outflow = sum of all water outflow components besides transpiration (kg).

Re-arranging formulation (2.1), we get

$$T = \text{Inflow} - \text{Other outflow} - \delta W. \qquad (2.2)$$

At the field level, examples of inflows are irrigation and rainfall and examples of other outflows are evaporation and deep percolation beyond the rootzone. Crop growth and transpiration are dynamic processes and need to be considered over time. The amount of water available for transpiration is not only determined by the amounts of daily inflows and outflows, but also by the size of the storage pool. This size determines the 'buffering capacity' of the system: a surplus of water inflow can be stored and be available to the crop at later times when there is a deficit of water inflow. Taking this buffering capacity into account, formulation (2.2) becomes

$$T = C_s(\text{Inflow} - \text{Other outflow}) - \delta W, \qquad (2.3)$$

where

- C_s = storage factor (–).

The storage factor in formulation (2.3) is a dimensionless and conceptual term affecting the size of all outflow terms (though in different degrees).

Combining formulations (1) and (2), we get a generic description of crop production in terms of water use:

$$\begin{aligned}\text{Production} &= [WP_T] \times [T] \\ &= [Y/T] \times [C_s(\text{Inflow} - \text{Other outflow}) - \delta W]\end{aligned} \qquad (3)$$

Water productivity term (1)

Storage size term (2)

Inflow term (3)

Non-transpirational outflow term (4)

Storage change term (5)

The objectives to increase total crop production and to minimize the use of scarce/expensive irrigation water can be realized by the following four "principles":

1. Increase transpirational crop water productivity.
2. Increase the storage size in space or time.
3. Increase the proportion of non-irrigation water inflows.
4. Decrease the non-transpirational water outflows.

Water for transpiration can also be met by depleting the storage pool (δW is then negative), but, on the long run, this is unsustainable. Any refilling of the storage pool should be included as Inflow in formulation (3). The analysis of crop production and water scarcity can be addressed at different spatial scales, for example plant, field, farm to regional or basin level. A systems approach is useful in defining the terms of the production formulation and identifying strategies to implement the generic principles at the different scales. In a systems approach, the boundary conditions define the components of inflow and outflow, the nature and size of the storage pool, and determine which of the flow rates are internally or externally determined. In the following sections, formulation (3) and the four generic principles are elaborated for three scale levels: plant, field, and (small) agricultural landscape. Examples are given for extreme hydrological environments ranging from semi-arid in sub-Sahara Africa to flooded rice in monsoon Asia.

3. Plant level

For an individual plant, formulation (3) can be written as

$$\text{Production} = \left[\text{HI}_{\text{plant}} \times B_{\text{plant}}/T_{\text{stomata}}\right] \times [C_{\text{s}}(\text{root water uptake} - T_{\text{cuticle}})], \quad (4)$$

where

- HI_{plant} = harvest index of the plant (kg kg^{-1}),
- B_{plant} = biomass of the plant (kg),
- T_{stomata} = transpiration through leaf stomata (kg),
- T_{cuticle} = transpiration through leaf cuticle (kg).

The system boundaries are formed by the outside of the plant above and below ground (Fig. 1). The storage unit is the plant itself. The only water inflow into the system is water taken up by the roots and the only outflow is water transpired, which can be divided into transpiration through the stomata (T_{stomata}) and transpiration through the cuticle (T_{cuticle}). The only internal water flow is vertical (upward) movement of water in the plants from the roots to the leaves. The four principles to increase production and minimize irrigation water can be implemented only through genetic improvement of the plant.

3.1. Increasing transpirational crop water productivity (WP_T)

Bennet (2003) recently presented an overview of options to increase WP_{T} through genetic improvement. There are basically two possibilities: increasing the

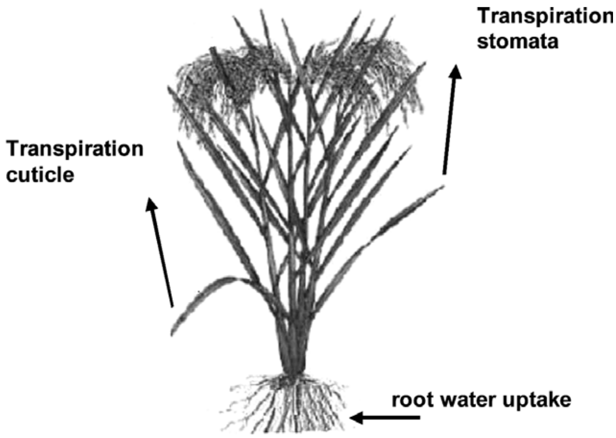

Fig. 1. Water flows and system boundaries at the plant level; example for a rice plant.

net photosynthesis per unit transpiration through the stomata, or by increasing the harvest index. Acevedo and Ceccarelli (1989) proposed that improved carboxylation efficiency and stomatal adjustment (under drought) could increase the photosynthesis/transpiration ratio. Knowledge about stomatal regulation and its underlying genetic mechanisms is rapidly increasing which may lead to breakthroughs in the future. Peng et al. (1998) demonstrated that some improved tropical *japonica* lines of rice have 25–30% higher rates of photosynthesis over transpiration than older *indica* varieties, suggesting that breeding may have played a role in improving this characteristic. In Australia, a wheat breeding program that selected specifically for high transpiration efficiency, using carbon isotope discrimination techniques, resulted in yield increases of 2–23% compared with control cultivars (Passioura, 2006; Richards, 2006). Genetic variation in carbon isotope discrimination was also reported for barley (Acevedo and Ceccarelli, 1989) and sunflower (Richards, 2006). Another improvement in transpiration efficiency may be the conversion of C_3 plants into C_4 plants through genetic engineering. C_4 Plants are more efficient in their photosynthetic pathway and may also have a higher water use efficiency than C_3 plants. However, the feasibility and potential benefits of this transformation are still debated (Sheehy et al., 2000).

The varieties of the green revolution have demonstrated the success in increasing the harvest index through breeding (Khush, 2001). The harvest index can be increased by manipulation of the plant architecture, namely ‘dwarfing’, and by increasing the amount of assimilates allocated to the plant organ of economic interest. The dwarfing genes for cereals have been successfully identified and may be exploited to obtain similar gains in harvest index in other crops (Bennet, 2003). A special consideration is a plant’s ability to maintain a high harvest index under drought at flowering (Saini and Westgate, 2000; Passioura, 2006). Bennet (2003) gives an overview of recent advances in, and prospects for, genetic improvement of harvest index. Though current achievements are small, a noticeable success is the development of maize varieties with reduced anthesis-silking interval, which have shown yield increases in drought environments of more than 10% through a high spikelet fertility and successful grain set per plant (overview by Richards, 2006).

3.2. Increasing storage size

Although certain cacti and orchids do have an efficient system of internally storing water (cacti throughout their body, and orchids through their special spongy root structure), increasing the internal water storage of agricultural plants is not an option.

3.3. Increasing the proportion of non-irrigation water inflows

The plant does not distinguish between the sources of water at its roots and there are no options to specifically increase non-irrigation water uptake.

3.4. Decreasing the non-stomatal water outflows

Water transpired through the cuticle is not directly productive, although it does contribute to cooling and maintaining the sap flow that transports nutrients and biosynthetic products from roots to leaves. An option to decrease cuticular transpiration is to increase the waxiness of the leaf surface. For example, rice has thin cuticles, with less than 5% of the wax load of other crops, and cuticular resistance is comparatively low (Lafitte and Bennet, 2002). More understanding of the water loss through the cuticle is needed before improvements in this area can be expected.

4. Field level

At the field scale, formulation (3) can be written as

$$\begin{aligned}\text{Production} = {} & [\text{HI} \times B_{\text{crop}}/T_{\text{crop}}] \\ & \times [C_{\text{s}}((I + R + C + S_{\text{in}} + R_{\text{on}}) - (E + T_{\text{weed}} + S_{\text{out}} + P + R_{\text{off}}))].\end{aligned} \quad (5)$$

The system boundaries are the top of the crop and the bottom of the rootzone in the vertical plane, and the field boundaries in the horizontal plane (Fig. 2). The storage unit is the rooted soil volume plus any storage on the surface of the soil. The water inflows into the system are irrigation (I), rainfall (R), capillary rise from groundwater (C), lateral subsurface inflow (S_{in}) and runon (R_{on}). The water outflows from the systems are evaporation from soil or (as in the case of irrigated rice) ponded water (E), transpiration by the crop (T_{crop}), transpiration by weeds (T_{weed}), lateral subsurface outflow (S_{out}), deep percolation (P) and runoff (R_{off}). Internal water flows are horizontal movement of water over the soil surface, horizontal and vertical movement of water in the rootzone, and vertical (upward) movement of water in

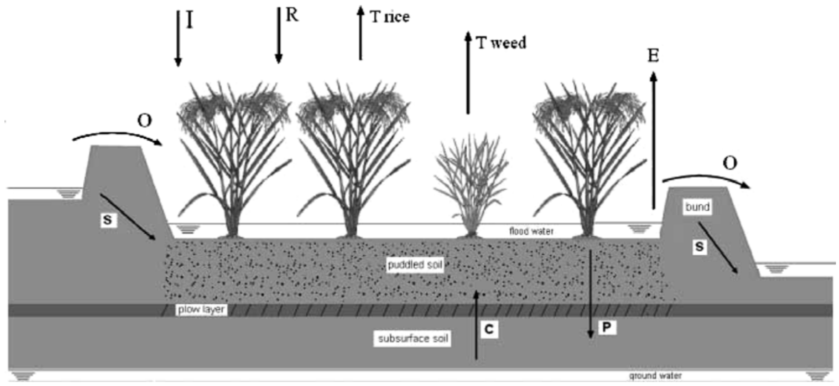

Fig. 2. Water flows and system boundaries at the field level; example for a flooded rice field. C = capillary rise from groundwater, E = evaporation from the soil/water surface, I = irrigation, O = overbund flow (runon/runoff), P = percolation, R = rainfall, S = lateral seepage, T_{rice} = transpiration by rice, T_{weed} = transpiration by weeds.

the plants (from root to leaves). Finally, B_{crop} is the biomass of the whole crop, and T_{crop} is the transpiration by the crop. The four principles to increase production and minimize irrigation water can be implemented by improvement of the germplasm and/or in crop and field management.

4.1. Increasing transpirational crop water productivity (WP_T)

There are no direct options to improve the WP_T, or transpiration efficiency, of germplasm at the field level other than those at the plant level. Although there are many options to increase biomass production through improved management, the ratio of biomass production over transpiration has been shown to be fairly constant for a given species in a given climate (De Wit, 1958; Ehlers and Goss, 2003). However, there are options to increase WP_T by growing crops in a cooler climate. A crop grown in dry and hot weather will transpire more than the same crop grown in cool weather (based on thermodynamic principles, a high temperature and a large vapor pressure deficit promote transpiration). It has been demonstrated in Mediterranean climates that sowing of crops such as wheat, barley and chickpea in late autumn/early winter rather than in spring, increased transpiration efficiency and yield (Richards, 2006; Ceccarelli et al., 1991). The success of this strategy was based on the development of crop varieties with increased cold tolerance and increased duration, which may be considered as indirect crop improvements to increase WP_T.

Crop management can be adapted to increase harvest index under drought. "Crop rationing" refers to strategies that aim to accumulate sufficient biomass early in the season without depleting available soil water to the extent that shortages occur later in the season (Debaeke and Aboudrare, 2004). With a short vegetative phase and an early flowering time, enough water may be left in the soil to guarantee a high harvest index. The drawback is that not enough biomass may have been formed to set a large number of seeds. With a late flowering date, more biomass can be accumulated but the harvest index may be low because of water shortages in the reproductive phase. An optimal flowering time balances the amount of water available during canopy development and during the reproductive phase. For many crops, breeders have produced a range in cultivars with different flowering time and growth durations to fit different environments (Passioura, 2006). In fact, the development of high-yielding short-duration varieties has been one of the most successful mechanisms to increase crop production in drought-prone environments (Bennet, 2003). Recent advances in genetics are revealing major genes and Quantitative Trait Loci associated with the control of flowering time, which may be used in further exploitation of this trait in drought-prone environments (Bennet, 2003). The harvest index of crops can also be manipulated by irrigation and fertilization. With supplemental irrigation, small amounts of irrigation are carefully applied at critical times of the growing season, such as at flowering and grain filling, to maintain a high harvest index (Oweis and Hachum, 2003). Nutrient management should aim at striking the right balance between fertilization in the vegetative phase and at flowering or grain filling. Too much nitrogen in the vegetative phase may result in a vigorous crop that sets a large number of seeds, but that depletes soil water too fast before flowering and that may not be able to fill the seeds (Passioura, 2006).

4.2. Increasing storage size

Increasing the root length of plants was proposed by Blum (1988) as an efficient breeding strategy to allow crops to tap water stored in deeper soil layers. For rainfed lowland rice, the capacity of roots to penetrate the hardpan underneath the puddled layer at times of drought may be a special breeding target (Ray et al., 1996). So far, however, breeders have had little success in developing varieties with improved root systems. Passioura (2006) commented that there must be genetic variation in the ability of crop roots to exploit subsoils, but that no obvious traits have been identified yet that breeders could select for. On the other hand, there are many agronomic practices to increase the storage size of the rootzone. Tillage options are the breaking of hard pans, deep plowing and subsoil ripping (Ehlers and Goss, 2003). Appropriate fertilizer application has been shown to increase root length and depth (Debaeke and Aboudrare, 2004). In semi-arid agriculture, a bare fallow period can be used to store water during one foregone cropping season for use in the next (this practice extends the storage size in time rather than in space). The efficacy of this practice is variable and depends on soil depth, structure and texture, the control of weeds, and the amount of runoff or soil erosion during the fallow period (Debaeke and Aboudrare, 2004; Passioura, 2006).

4.3. Increasing the proportion of non-irrigation water inflows

Varieties with longer roots may be able to capture shallow ground water through capillary rise. The use of early flowering and short-duration varieties reduces the length of the growing season and helps in escaping late or end-of-season drought (see above). Although not more rainfall is captured in absolute terms, in relative terms more rainfall is captured per growing day.

More rainfall can be captured by better adjustment of the cropping pattern to the rainfall season. In wet-season rice, direct dry seeding can advance the growing season and utilize early-season rainfall more effectively than transplanted systems (Cabangon et al., 2002; Tabbal et al., 2002). In the semi-arid regions of West Asia and North Africa, shifting from summer cereals to winter cereals allows the efficient use of winter and early spring rainfall (Oweis and Hachum, 2003). Timeliness of crop establishment has greatly increased the last decades with the rapid changes in mechanization, such as the development of zero-till machinery (Hobbs and Gupta, 2003; Passioura, 2006). Within a field, rain water can be captured more efficiently by adjusting the crop density and spatial arrangement of plants. Crops can be planted in slight natural depressions where rainfall accumulates, or runoff water may be redirected to areas where crops are planted (Van Keulen, 1975). Whole fields, sections of fields or even individual plants can be bunded to capture rainfall and make it better available to the crop (this strategy can also be seen as increasing water storage). With light rainfall, plowing and harrowing the soil reduces runoff and promotes infiltration (Falkenmark and Rockström, 2004). With heavy or high-intensity rainfall, plowing can promote surface sealing and have the opposite effect. In that case, zero or minimum tillage are better alternatives. Also, Debaeke and Aboudrare (2004) commented that deep plowing may store more water during rainy periods, but, compared with shallow tillage or zero tillage, may accelerate soil evaporation during dry periods. Deep soil ripping with minimum topsoil disturbance again promotes infiltration and deep rooting by the crop.

There are two irrigation strategies that do not increase the amount of non-irrigation water use in absolute terms, but, by minimizing irrigation water use, increase the proportion of non-irrigation water use. With supplemental irrigation, small amounts of irrigation are carefully applied at critical times of the growing season when rainfall is insufficient (Oweis and Hachum, 2003). In deficit irrigation, less irrigation is applied than required to realize maximum crop production (Oweis and Hachum, 2003; Zhang and Oweis, 1999).

4.4. Decreasing the non-transpirational water outflows

Non-productive water outflows can be high in many different cropping systems. Falkenmark and Rockström (2004) estimated that in the semi-arid tropics of sub-Sahara Africa, about 10–25% of rainfall flows out of a field as runoff, 10–30% as deep percolation, 30–50% as evaporation, and only 15–30% as crop transpiration. In flooded rice fields in Asia, outflows of water by seepage and percolation account for about 25–50% of all water inputs in heavy soils with shallow water tables of 0.2–0.5 m depth (Cabangon et al., 2004; Dong et al., 2004), and 50–85% in coarse textured soils with deep water tables of 1.5 m depth or more (Sharma, 1989; Sharma et al., 2002; Singh et al., 2002). Therefore, a lot of emphasis has been placed on developing technologies that reduce these non-beneficial outflows.

Many of the on-farm water harvesting techniques described earlier to increase the inflow of rain water also reduce the evaporation and runoff outflows. Soil evaporation can be reduced by developing plants that display early vigor or have a prostrate growth habit (Acevedo and Ceccarelli, 1989). Early planting, high density and close row spacing stimulate early crop cover and increase the transpiration/evaporation ratio (Debaeke and Aboudrare, 2004). Mulching by covering the soil with crop (or weed) residues reduces the amount of solar energy falling on the soil which reduces evaporation. This form of mulching also reduces runoff and promotes infiltration of rain water into the rootzone. In north China, plastic sheets are extensively used to cover the soil in crops such as water melon and cotton, and researchers are experimenting with their use in rice cultivation (Dittert et al., 2002; Shan Lin et al., 2002). Another form of mulching consists of shallow soil harrowing to create a hydraulic discontinuity between the loosened topsoil and the undisturbed subsoil that limits the upward movement of water. In irrigated agriculture, precision techniques such as drip or sub-surface irrigation bring water close to the roots of the crop and reduce the wetted surface area of soil and hence reduce evaporation. However, these systems require additional effort, management skills and investments.

In rainfed conditions, the scope to reduce percolation flows is relatively limited. In irrigated agriculture, sprinkler, drip and sub-surface irrigation can be used to control the volume and intensity of applied water and thus limit percolation losses. With surface systems such as basins and furrows, under-irrigation may be effective to reduce percolation losses. Management measures to reduce percolation from irrigated rice fields are alternate wetting-and-drying, direct seeding, saturated soil culture, soil compaction, land leveling, and aerobic rice (Bouman and Tuong, 2001; Tuong and Bouman, 2003; Tuong et al., 2005). In flooded rice, seepage through bunds can also be quite large and good maintenance (e.g., closing rat holes, regular plastering and compaction) can help reduce seepage losses.

Transpiration by weeds can be reduced by breeding crop varieties that are effective weed suppressants (Bennet, 2003). Developing herbicide-resistant varieties is another appropriate breeding strategy. Management options to control weeds are the use of herbicides, mechanic and manual weed removal, crop rotation, soil tillage and general phytosanitation measures.

Good crop management can contribute indirectly to the reduction of various non-productive outflows. A strong and healthy growing crop produces al large amount of biomass that makes transpiration a strong "competitor" for water relative to the other outflows. For example, Breman et al. (2001) and Oweis and Hachum (2003) showed that, in semi-arid climates, increased nutrient applications increased biomass growth, crop water uptake and crop water productivity with respect to evapotranspiration (WP_{ET}). For the same environments, Falkenmark and Rockström (2004) concluded that increased WP_{ET} through improved crop management is mainly realized by a shift from (less) soil evaporation to (more) crop transpiration. Beside water, nutrient and weed management, the control of pests and diseases contributes to a vigorous and healthy canopy. Passioura (2006) concluded that breeding for resistance against leaf and root diseases contributed indirectly to improved water productivity in Australia. Any measure that increases crop transpiration early in the season, however, should be evaluated against the risk of depleting soil water reserves too fast so that water shortages occur later in the season (Debaeke and Aboudrare, 2004). In this respect, improvements in weather forecasts can help farmers make timely and well-informed decisions.

5. (Small) agricultural landscape

A small agricultural landscape consists of a number of fields that may be hydrologically connected, such as in Fig. 3 for a series of rice fields. Such a landscape may consist of a single large farm such as in extensive cropping systems in semi-arid areas, or of a large number of small farms such as in Monsoon Asia. The single, or dom-

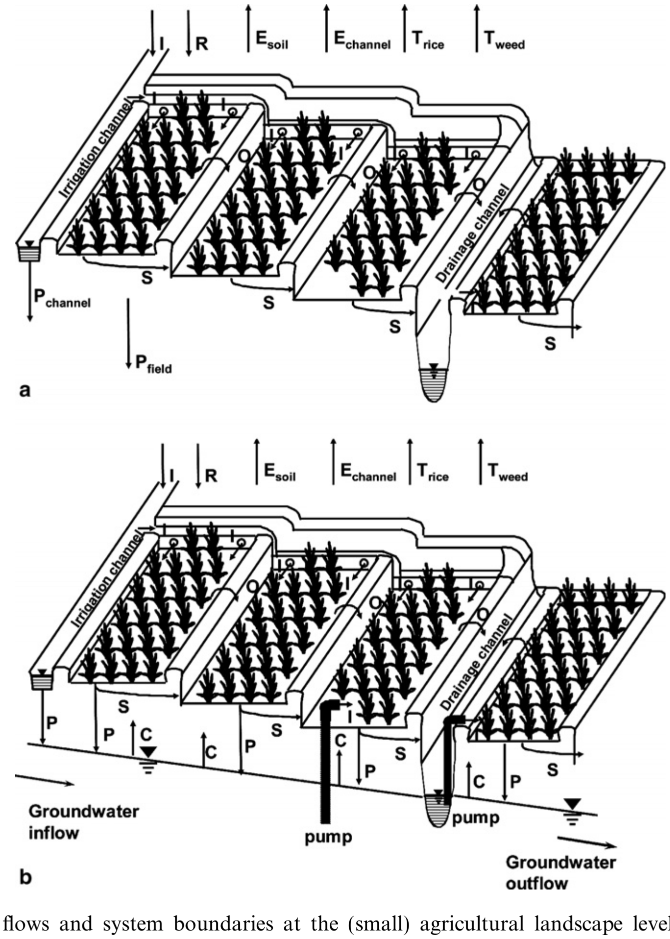

Fig. 3. Water flows and system boundaries at the (small) agricultural landscape level; example for a cascading series of rice fields with deep groundwater (a) and with shallow groundwater included in the system (b). C = capillary rise from groundwater, $E_{channel}$ = evaporation from water in the channels, E_{soil} = evaporation from the soil surface, I = irrigation, O = overbund flow (runon/runoff), $P_{channel}$ = percolation from channels, P_{field} = percolation from fields, R = rainfall, S = lateral seepage, T_{rice} = transpiration by rice, T_{weed} = transpiration by weeds.

inant, water user in this landscape is agricultural crops. The elaboration of formulation (3) depends on whether a groundwater aquifer is included in the system and used as water resource or not. With deep or unexploited groundwater (Fig. 3a):

$$\text{Production} = [\text{HI} \times B_{\text{crop}}/T_{\text{crop}}] \times [C_s((I + R + S_{\text{in}} + R_{\text{on}}) - (E_{\text{soil}} + E_{\text{channel}} + T_{\text{weed}} + S_{\text{out}} + P_{\text{field}} + P_{\text{channel}} + R_{\text{off}}))]. \quad (6a)$$

With exploited shallow groundwater (Fig. 3b):

$$\text{Production} = [\text{HI} \times B_{\text{crop}}/T_{\text{crop}}] \times [C_s((I + R + S_{\text{in}} + R_{\text{on}}) - (E_{\text{soil}} + E_{\text{channel}} + T_{\text{weed}} + S_{\text{out}} + R_{\text{off}}))], \quad (6b)$$

where E_{channel} is evaporation from water in open channels within the spatial domain of analysis, E_{soil} is evaporation from the soil, P_{channel} is percolation from the channels, and P_{field} is percolation from fields (all other abbreviations same as in formulation (5)). The implications for application of the four principles between the two groundwater scenarios are discussed below.

5.1. Increasing transpirational crop water productivity (WP_T)

There are no specific options to increase WP_T at this scale level.

5.2. Increasing storage size

The use of a ‘‘secondary’’ storage pool to store water either on or below the surface is probably the most important option. Rainwater can be harvested by directing surface runoff into reservoirs that may vary in size from small on-farm ponds or cisterns for supplementary irrigation (Falkenmark and Rockström, 2004), to village level ponds or tanks such as in Sri Lanka and southern India. Reservoirs may also be used to collect internal drainage water (seepage, runoff) from fields upstream within the system and make it available for downstream use. For example in Zanghe Irrigation System in Hubei, China, thousands of on-farm and village-level ponds have been constructed to capture drain water coming out of rice fields (Mushtaq et al., 2006). These reservoirs have greatly contributed to maintaining the volume of rice produced in the irrigation system, despite the fact that agricultural water allocations from the main reservoir dropped from about 80% in the mid-60s to around 25% in the early 90s (Loeve et al., 2004a,b). In irrigation systems, seepage and drainage water is quite often collected in ditches, drains and canals from where it can be reused by pumping.

Besides these surface reservoirs, underground aquifers can also be exploited as secondary storage. Since the introduction of relatively cheap small pumps in the 90–70s, millions of farmers (especially in Asia) have dug shallow tube wells to exploit underground water (Fig. 3b). Especially in rice-based cropping systems, groundwater tables can be very shallow and pumping costs low (Belder et al., 2004; Cabangon et al., 2004). A study in an irrigation system in the Philippines showed that up to 20% of irrigation water applied by surface irrigation was reused by farmers through pumping from secondary storage pools such as groundwater and drains (Hafeez, 2003). Another study of a rice-based irrigation system in Japan showed that 14–15% of the total irrigation water supply was reused within the system (Zulu et al., 1996).

5.3. Increasing the proportion of non-irrigation water inflows

Rainwater use can be increased by water-harvesting in reservoirs as explained below.

5.4. Decreasing the non-transpirational water outflows

Evaporation from water surfaces in canals and channels can be reduced by using piped or covered conveyance systems. The options to reduce evaporation from bare soil and transpiration from weeds were discussed at the field level. Surface runoff and seepage outflows that are losses from one field may be runon and seepage inflows for another field, respectively. It is only at the boundaries of the system that runoff and seepage outflow occurs and that measures can be taken to reduce these flows (same as at field level). Another strategy is to capture these flows in secondary storage and make them available for reuse (see above).

When groundwater is deep (Fig. 3a), percolation from fields, canals and channels are lost to the system. Canal percolation losses can be reduced by various forms of lining or soil compaction; options to decrease percolation from fields are discussed above. With an exploited shallow groundwater (Fig. 3b), percolation flows from both the fields and canals are internal flows that recharge the secondary storage pool (groundwater) and are physically not lost to the system. The costs of reusing this water, e.g. by pumping, should be compared with the costs of measures to reduce these percolation flows.

6. Conclusion and discussion

The conceptual framework and the four key principles presented here are useful to identify interventions to increase crop production and save scarce or expensive water resources at the same time. The framework can help analyze and understand the underlying mechanisms of technologies that enhance crop water productivity. This understanding, in its turn, can help identify extrapolation domains for such technologies and estimate their potential in meeting (future) food demands through a wise use of water. The few examples presented here to illustrate the framework are far from exhaustive. They also do not suggest overall best-bet options and do not make general quantifications of potential water savings since these are extremely site-specific. They do, however, disentangle complex underlying relationships. Sometimes, a technology incorporates more than one key principle. A case in point is within-field water harvesting that reduces the non-productive outflows runoff and evaporation and increases the inflow of rainwater into the rootzone for subsequent crop transpiration. The examples also show the added value of combining technologies, such as the introduction of water harvesting with supplementary irrigation (Falkenmark and Rockström, 2004). Another example is the combination of breeding with natural resource management strategies, such as early winter sowing of cold-resistant varieties of cereals in Mediterranean and semi-arid climates (Oweis and Hachum, 2003; Passioura, 2006). Next steps are to apply the framework to specific case studies and to turn the conceptual framework into an analytical one by quantifying water flows through measurements or simulation modeling.

The framework is limited to a biophysical analysis of agricultural crops (quantitative yield) and does not include the quality or economic value of crop produce. It is mostly relevant for bulk food crops, such as cereals and tubers, and animal fodder crops, but probably less so for vegetables and fruits. Practical interventions that are suggested through application of the framework should be economically evaluated before implementation. This becomes especially relevant at spatial scales beyond the field where different crops with different economic values may be grown and allocation of water among crop types becomes an issue. Also, at larger spatial scales such as the landscape, the framework is limited to situations where crops are the only or dominant user of water. In landscapes with multiple users of water (e.g., domestic users, industry, livestock, nature), allocation of water among these users becomes more of an issue. In such situations, the water accounting framework as developed by Molden et al. (2003) is a more appropriate tool for analysis of water productivity than the framework presented here. However, both frameworks can complement each other in finding specific solutions for the agricultural water users in the landscape. A discussion of policy or institutional instruments that can be used to promote the adoption of such solutions (e.g., water pricing, water rights) or to effectively allocate water among different crops or users is beyond the scope of this paper (see for example Bruns et al., 2005, for recent overviews and case studies).

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