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Water for food and nature in drought-prone tropics: vapour shift in rain-fed agriculture

Johan Rockström

UNESCO-IHE, PO Box 3015, 2601 DA Delft, The Netherlands (*rockstrom@eng.uz.ac.zw*)

This paper quantifies the eco-hydrological challenge up until 2050 of producing food in balance with goods and services generated by water-dependent ecosystems in nature. Particular focus is given to the savannah zone, covering 40% of the land area in the world, where water scarcity constitutes a serious constraint to sustainable development. The analysis indicates an urgent need for a new green revolution, which focuses on upgrading rain-fed agriculture.

Water requirements to produce adequate diets for humans are shown to be relatively generic irrespective of hydro-climate, amounting to a global average of 1300 $m^3\ cap^{-1}\ yr^{-1}$. Present food production requires an estimated 6800 $km^3\ yr^{-1}$ of consumptive green water (5000 $km^3\ yr^{-1}$ in rain-fed agriculture and 1800 $km^3\ yr^{-1}$ from irrigated crops). Without considering water productivity gains, an additional 5800 $km^3\ yr^{-1}$ of water is needed to feed a growing population in 2050 and eradicate malnutrition. It is shown that the bulk of this water will be used in rain-fed agriculture.

A dynamic analysis of water productivity and management options indicates that large ‘crop per drop’ improvements can be achieved at the farm level. Vapour shift in favour of productive green water flow as crop transpiration could result in relative water savings of 500 $km^3\ yr^{-1}$ in semi-arid rain-fed agriculture.

Keywords: water productivity; rain-fed agriculture; evapotranspiration; savannah; food

1. INTRODUCTION

(a) *The challenge of balancing water for food and nature*

Mankind is faced with an unprecedented challenge of feeding a rapidly growing world population. The reason is, unlike the food crisis that Latin America and Asia were facing prior to the ‘Green Revolution’ in the 1960s, that the regions now facing the largest food needs are subject to four fundamental constraints that simultaneously affect the possibilities of producing enough food. These four include population growth, poverty, erosion of ecological and social resilience, and climate change. Even though UN projections indicate a decline in population growth rates, world population is estimated to grow by a further 2.9 billion people between now and 2050. At present, population growth is at a rate of 80 million people per year. Almost the totality of this growth, or 95%, occurs in developing countries. Today home to five billion of a global population of 6.2 billion people (2002), developing countries will, despite anticipated declines in fertility, host an estimated 8.2 billion people in 2050 (according to UN average projections).

Poverty and food are closely interlinked. Among the 1.2 billion extremely poor people (earning less than 1 US dollar per day) it is estimated that three-quarters make their living in rural areas. It is among the extreme poor we find the 800 million people who at present suffer from undernourishment. Severe rural poverty pushes rural inhabitants out of the rural areas. This rural exodus explains the estimate that over 50% of the world’s population is expected to live in coastal cities by 2025 (Falkenmark & Rockström 1993).

A food challenge now faces societies hosted in environmentally vulnerable landscapes (ICSU 2002). Added to this inherent ecological vulnerability is the human induced erosion of ecological resilience, i.e. the capacity of the natural resource base to absorb environmental shocks (that threaten the potential of producing food) and to generate ecosystem goods and services (Holling 1986). Agriculture is by far the world’s largest land use. Rain-fed agriculture dominates, accounting for 80% of cultivated land, while the remaining 20% is under irrigation. In sub-Saharan Africa, 95% of the cultivated land is under rain-fed agriculture, of which the bulk is small-holder farming. Land degradation, to a large extent water erosion in savannahs, affects *ca.* 60% of the rain-fed cropland in sub-Saharan Africa (Chou & Dregne 1993).

Moreover, the acceleration and large-scale impact of human-induced degradation is relatively recent, often occurring within the last century, and is caused largely by interacting pressures from population growth, poor land-management practices and weak land policies acting on a vulnerable natural resource base. Land degradation reduces the capacity of the agricultural ecosystems to absorb environmental shocks, such as floods and droughts. Furthermore, erosion from agricultural lands seriously affects the biodiversity and environmental health of aquatic ecosystems, thereby also reducing the capacity of natural ecosystems to buffer environmental shocks.

This is dramatic, as it suggests that in a situation where more food than ever before in human history is required

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to feed an increasing and hungry population, the natural resource base available to generate the necessary food is more vulnerable than ever before.

Last, it is now well established that human activities, especially those linked to the burning of fossil fuels, are having a major effect on the global environment (IPCC 2001; ICSU 2002). Projections indicate that climate change will result in a large increase in climatic shocks, such as floods and droughts, and lead to a progressive decline in overall rainfall especially in already drought-prone environments. This will have strong implications on food security, as agriculture is by far the world's largest direct water-dependent human activity. Mitigating droughts will therefore be even more important in the future. In the past, drought management has been strongly blurred and often politicized, as a result of confusions related to the definition of droughts and to the analysis of their causes and effects (Glantz 1994). This is unfortunate as efforts of mitigating droughts require a clear understanding of (i) when droughts actually occur, and (ii) a distinction between manageable droughts (where improved land management can assist in mitigation) and unmanageable droughts (when social and economic coping mechanisms, outside the managed landscape, are required).

(b) *Zooming in on a global hot spot*

These interacting thumbscrews, affecting the human potential to produce food in the regions of highest food demand, are rendering increasing attention with recent calls for a new green–green revolution (Conway 1997). From a water-management perspective a new green revolution would be more challenging than the previous success, as the core focus now must be on the resource of poor farm communities hosted in agro-ecosystems where water is a major constraint to food production and livelihood security. Of the world's rural inhabitants approximately half live in savannah agro-ecosystems where the hydro-climate is characterized by frequent droughts and floods. Savannahs, covering *ca*. 40% of the world's land area (UNEP 1992) host between 28–46% of the populations (both rural and urban) in poverty stricken regions of south and South East Asia, Latin America and Africa (Murray *et al.* 1999). Savannahs are ecosystems that lie between the forests and deserts of tropical regions (Huntley & Walker 1982). They have a pronounced annual rhythm of prolonged dry periods followed by short wet seasons (two to six months long). Rainfall variability is extremely high, making dry spells, droughts and floods a natural part of the ecosystem dynamics. Rainfall (P) ranges from 350 mm in the dry semi-arid shrub savannah to 1500 mm in the dry sub-humid parkland and woodland savannah. The atmospheric thirst is very high, with annual PET exceeding 1500 mm, and amounts of 600–800 mm during the rainy seasons when rain-fed crop growth occurs. Hydrologically savannahs generate only limited run-off at catchment and river basin scale, explained by the high aridity, with annual P/PET ratios ranging from 0.2–0.65 (UNESCO 1979). Savannahs are the largest agro-ecosystem hosting the sedentary resource of poor farming communities facing major water scarcity problems. In terms of balancing water for food and nature, savannahs in semi-arid and dry sub-humid hydro-climates emerge as a global hot spot.

In this paper the global challenge of securing water for food production in balance with nature is briefly outlined. Once the trade-offs between water for food and nature are quantified, the paper continues by investigating the options available to (i) secure food for growing populations in water-scarce tropics, and (ii) the opportunities of producing more food with relatively less water, i.e. improve water productivity or 'crop per drop' in order to simultaneously secure food and safeguard water-dependent ecosystems. While water productivity is discussed in a wide sense, as both the amount of water supplied and used to produce a unit of food, special attention is given to green water flow, or evaporation and plant transpiration flows, which generally are understood as the only real consumptive water flows in plant growth. Options of vapour shift are investigated, i.e. to reduce non-productive evaporation in favour of productive crop transpiration in agriculture. This vapour shift, from a system or catchment perspective is the only true 'crop per drop' improvement, as it carries no direct hydrological implications on downstream water using actors and systems.

2. GLOBAL FRESHWATER RESOURCES: WIDENING THE APPROACH

(a) *Ecosystem services from green and blue water flows*

Conventionally, only the portion of total run-off, or blue water flow, which constitutes stable run-off flow is considered as the freshwater resource in the terrestrial hydrological cycle upon which humans depend. This omits flood run-off flow, stagnant waters in seasonal wetlands, and vapour flow, or green water flow, which includes all evaporation fluxes (direct evaporation, interception and transpiration from plants). Accessible 'freshwater' (i.e. stable blue water flow) has been estimated at 12 500–15 000 $km^3\ yr^{-1}$ (Lvovich 1979; Postel *et al.* 1996), or 11–13% of total annual terrestrial precipitation, of which humans at present appropriate *ca*. 4000 $km^3\ yr^{-1}$, or 2% of total precipitation. This small portion of terrestrial precipitation is considered to be the total human freshwater withdrawal, and is used in irrigation, industry and for domestic purposes (Gleick 1993). We can define this as direct blue water withdrawals. Increasingly, there is an understanding that freshwater sustains other ecosystem goods and services upon which humans depend, such as biodiversity, forests, grasslands, wetlands and rain-fed crops (Postel 1998; Rockström *et al.* 1999; Jansson *et al.* 1999). It should be noted that recent water resource assessments do include both irrigated and rain-fed land use in estimates of present and future food production, but estimate the freshwater implications only in terms of stable run-off and blue water withdrawals (e.g. Shiklomanov 2000; de Fraiture *et al.* 2001; Rosegrant *et al.* 2002). Such blue water estimates suggest that freshwater withdrawals will increase from *ca*. 4000 $km^3\ yr^{-1}$ in 2000 to a range of 4300–5000 $km^3\ yr^{-1}$ in 2025 (Gleick 1997; Raskin 1997; Shiklomanov 1997, 2000; Raskin *et al.* 1998; Alcamo *et al.* 2000; Seckler *et al.* 2003). In recent years increased attention has been given to environmental water flows required to sustain aquatic ecosystems (Hughes &

Ziervogel 1998; King & Louw 1998). A recent attempt to map environmental water flow requirements in the world's major river basins suggest that between 30–50% of base run-off flow needs to be secured to sustain instream ecology (Revenga & Smakhtin 2003). The only global estimate so far of green water flows sustaining ecosystem services in major biomes was carried out by Rockström *et al.* (1999). They estimated human dependence on green water flow from agriculture (irrigated and rain-fed), wetlands, grasslands and forests to be 63 000 $km^3\ yr^{-1}$ or 88% of annual average vapour flow. Blue water flow, both stable and storm flow, sustains not only direct human needs but also generates a wide set of direct goods (such as freshwater fisheries) and indirect services (such as aquatic habitats). All in all this suggests, despite recent integration of rain-fed land use and instream ecology, that the conventional approach of only considering the stable blue water flow as the freshwater resource upon which humans depend, is extremely narrow. In terms of food production, a widened green–blue approach to water resources indicates the importance of focusing equally on food produced through irrigation and on food produced through rain-fed crops. Eighty per cent of the world's cropland is rain-fed, a figure that generally approached 95% in savannah environments (Rockström 2000). Even though rain-fed agriculture contributes globally with an estimated 60% of world food (due to lower yield levels in rain-fed crop production), rain-fed agriculture will continue in the foreseeable future to be the dominant source of food (Parr *et al.* 1990).

(b) *Present water for food*

A starting point in assessing water trade-offs, between food and other ecosystem goods and services, is to estimate consumptive water-use requirements to produce present and future human diets. Based on UN (FAO) data on average human diets in different regions of the world and average water productivity data for different food components of diets, Gleick (2000) estimated that a European and a North American diet required (in the late 1980s) 1700–1800 $m^3\ cap^{-1}\ yr^{-1}$ to produce, while an African or Asian diet only required between 600–900 $m^3\ cap^{-1}\ yr^{-1}$ (of consumptive green water). The difference was largely explained by calorie intake; exceeding 3200 $kcal\ cap^{-1}\ d^{-1}$ in the former and being lower than 2700 $kcal\ cap^{-1}\ d^{-1}$ in the latter regions, and to the low proportion of water intensive (i.e. grain based) meat production in developing countries. These data give a world average of 1220 $m^3\ cap^{-1}\ yr^{-1}$ of consumptive green water to produce present diets. Rockström *et al.* (1999) arrived at a global average of 1200 $m^3\ cap^{-1}\ yr^{-1}$ to produce food in the mid-1990s, based on water productivity estimates and agricultural production only.

Assessing future water for food requirements based on water needs to generate diets has the advantage of enabling an analysis of all food types eaten by humans in different regions (grains, vegetables, fruit, nuts, fat, dairy products, meat etc.). Water requirements to produce food will on average vary between different crops as shown in table 1 for different food types in developing countries. The weighted average green water requirement to generate the plant-based part of diets in developing countries amounts to 0.53 m^3 1000 $kcal^{-1}$. The corresponding average for developed countries was 0.41 m^3 1000 $kcal^{-1}$, with the difference largely explained by the type of sugar crop—sugar beets instead of sugar cane—and a much larger consumption of sugar in developed countries. The weighted global average was 0.5 m^3 1000 $kcal^{-1}$ as a result of the large proportion of people living in developing countries.

Table 1. Estimated volumes of water (consumptive use of green water) to produce plant foods in developing countries.

food type	$m^3\ kg^{-1}$	m^3 1000 $kcal^{-1}$
cereals	1.5	0.47
starchy roots	0.7	0.78
sugar crops	0.15	0.49
pulses	1.9	0.55
oil crops	2	0.73
vegetable oils	2	0.23
vegetables	0.5	2.07
average		0.53

Water requirements for meat have been estimated to be *ca.* 5 m^3 1000 $kcal^{-1}$ based on grain-fed meat-producing cattle where energy conversion efficiencies are less than 20% (Pimentel & Houser 1997; Gleick 2000; W. Klohn, personal communication). However, this is a doubtful approach as large amounts of the meat, especially in the developing world, originate from cattle fed on grass from free grazing. It is difficult to attribute vapour flow required to generate grass grazed by livestock, as the water sustaining these ecosystems (mainly grasslands and woodlands) generate other ecosystem services than only grass (biodiversity, carbon assimilation, habitat for flora and fauna). As shown by Rockström (2003), an estimated 20 400 $km^3\ yr^{-1}$ of vapour flow is required to sustain permanent grazing areas in the world. This is a large portion of terrestrial green water flow, which would translate to a staggering range of 10–30 m^3 1000 $kcal^{-1}$ of meat (if calculated on estimates of present meat content in diets of *ca.* 360 $kcal\ cap^{-1}\ d^{-1}$ and 860 $kcal\ cap^{-1}\ d^{-1}$ in developing and developed countries, respectively, and assumptions on the proportion of grazing-based meat production). This indicates the difficulty of attributing consumptive water flow in meat production. Due to the multiple ecological functions of grazed ecosystems, it seems reasonable to assume a water requirement similar to the grain-based meat production. In this paper a water requirement of 4 m^3 1000 $kcal^{-1}$ of meat is adopted to reflect the multiple functions of grazing areas and the lower water requirement for poultry.

(c) *Desired water for food needs*

Based on the dietary water requirements above, it is possible to estimate future water for food needs. A desired average diet in developing countries in 2050 of 3000 $kcal\ cap^{-1}\ d^{-1}$ is assumed, which corresponds to the same level that FAO predicts as a global average in 2030. If we further assume that 20% of this is meat foods (a low figure compared to the present meat consumption of 30–35% in developed countries but slightly higher than the present average of 10–15% in developing countries), we arrive at a water requirement of 1300 $m^3\ cap^{-1}\ yr^{-1}$ to generate a desired diet of 3000 $kcal\ cap^{-1}\ d^{-1}$. For developed countries, the water for food requirements will most likely remain higher, as it is unlikely that average diets will reduce from the present 3300 kcal cap^{-1} d^{-1}. In this analysis it is assumed that the present calorie intake in developed countries will persist, with 30% of the diet originating from meat products, resulting in a desired water for food requirement of 1600 m^3 cap^{-1} yr^{-1}. The weighted global average amounts to 1340 m^3 cap^{-1} yr^{-1}, which remains close to the desired water diets for developing countries as the bulk of the world population is concentrated here (86%).

(d) *Generic water for food needs*

The dividing line, so far, in estimating water for food needs has been between developed and developing countries (due to different levels of dietary intake). Even though a vast majority of developing countries are hosted in tropical hydro-climates, the question arises as to whether water for diets is predominantly determined by evaporative demand (i.e. agro-climatic zone) and not by dietary composition (as the above analysis implicitly suggests). It is generally taken as a rule that more consumptive water (green water or vapour flow) is required to produce food in tropical ecosystems than in temperate ecosystems, as a result of higher atmospheric demand for water in tropical climates. However, there is limited evidence to support this assumption, at least for grains that constitute more than 50% of the diet in developing countries. Instead, from a biophysical perspective (excluding, for the moment, management), it seems more likely that one can speak of a *generic* water requirement to produce human diets, irrespective of a hydro-climatic zone. The reason is that the increase in productive vapour flow (crop transpiration) from food crops in tropical climates because of high evaporative demand is largely compensated for by more efficient photosynthetic pathways (e.g. C_4 plants in tropical environments compared with C_3 plants in temperate zone crops), which results in higher crop growth per unit of transpiration flow. It has been shown that C_4 crops have roughly twice as high carbon assimilation per unit of transpiration compared with C_3 crops, and interestingly, this assimilation rate, for a given climatic setting (determined largely by the vapour pressure deficit in the crop stand), is rather conservative for different crops. This means that for temperate food crops a less efficient photosynthetic pathway is compensated for by a more moist atmosphere (i.e. a lower pressure gradient is driving transpiration). The result is a generic transpiration use efficiency, i.e. rate of plant growth per unit of productive green water flow, which is in the order of 2–3 kg biomass mm^{-1} ha^{-1} (or 300–500 m^3 ton^{-1} biomass) (Loomis & Connor 1992; Ong *et al.* 1996). There are, of course, substantial variations in crop growth per unit of transpiration between crop species, and fluctuations in reported transpiration efficiencies among the same species. However, in general terms, there is ample evidence to suggest a relatively limited fluctuation in transpiration efficiency for grains (Wallace & Batchelor 1997; Sinclair *et al.* 1984; Rockström & Falkenmark 2000).

Even when evaporation flow is considered, the total consumptive water requirements to produce grain crops is *on average* surprisingly similar between hydro-climatic zones. The process-related factors explaining this will be discussed in the following sections. Table 2 shows green water productivity data (volume of evapotranspiration per unit crop) for a range of temperate and tropical crops. Interestingly, the range for most cereal crops is between 1000–2000 m^3 of green water flow to produce 1 ton of grain. Even for rice, many systems in the world operate at this range. Tubers, such as potatoes, are generally more water efficient, with less than 1000 m^3 required per ton of dry matter of potato. Tomatoes are another example of a highly water productive crop.

The conclusion is that, in generic terms, disregarding the impact of management, it would seem possible to talk of a relatively universal average of some 1500 m^3 of green water to produce 1 ton of food based on present genetic plant materials used by farmers (equivalent to 150 mm t^{-1} ha^{-1}).

However, as will be shown in § 6, there are large management opportunities to influence these figures. The range of actual green water use in the farmer's field is huge, often between 1000–6000 m^3 ton^{-1} (or 100–600 mm t^{-1} ha^{-1}) for a given crop within a given hydro-climate. This range, for one crop within a certain hydro-climate, is larger than the average range for different crops in different hydro-climates shown in table 2.

This suggests that the negotiable part of crop water needs—which can be influenced by management—induces a larger variation in crop water requirements than the non-negotiable biophysical parameters: related to hydro-climate and crop physiology and that cannot be influenced by the farmer. In the search for strategies where more food is produced with minimum impact on water availability for ecosystems, this is encouraging. It shows that management can offer large opportunities to change the current water use in agriculture. Win–win synergies where more food is produced per unit of consumed water are in contrast to the common notion that crop water requirements are always high and impossible to influence in hot tropical agro-ecosystems.

3. CAN THE WATER FOR FOOD NEEDS BE MET?

Based on the present (1200 m^3 cap^{-1} yr^{-1}) and desired (1300 m^3 cap^{-1} yr^{-1}) water needs for human diets it is possible to project future water requirements. Present consumptive water use in irrigation amounts to an estimated 1800 km^3 yr^{-1} (Shiklomanov 2000). Rockström *et al.* (1999) estimated consumptive water use in rain-fed agriculture to be 5000 km^3 yr^{-1}, giving a total green water use for food (which is assumed at the 'present' situation) of 6800 km^3 yr^{-1} (table 3). The water for food challenge involves both feeding a growing population and eradicating current under-nourishment (affecting 800 million people). The additional green water need to lift diets to desired levels would require an additional 2200 km^3 yr^{-1} (table 3), while feeding an additional 2.9 billion people would require 3600 km^3 yr^{-1}, resulting in a cumulative water for food requirement in 2050 of 12 600 km^3 yr^{-1}.

The projection in table 3 suggests a water deficit of 5800 km^3 yr^{-1}, which needs to be mobilized for consumptive use in agriculture over the coming 50 years in order to secure food for under-nourished and growing populations. This corresponds to more than three times the present consumptive use of water in irrigation. The additional water can come from both blue and green water sources.

Table 2. Water productivity (m^3 of green water flow per metric ton of grain) and crop water requirements (mm) for major food crops of the world.

crop	hydro-climate	crop type	water productivity ($m^3\ t^{-1}$) range		average	source
wheat	temperate	C_3	780	2640	1480	Rockström *et al.* (1999)
wheat	temperate	C_3	900	2000		Gleick (2000)
barley	temperate	C_3	540	1580	1000	Rockström *et al.* (1999)
rye	temperate	C_3	540	2640	1270	Rockström *et al.* (1999)
oats	temperate	C_3	540	2640	1370	Rockström *et al.* (1999)
rapeseed	temperate	C_3	1530	2030	1780	Rockström *et al.* (1999)
temperate cereals	temperate	C_3	660	2300	1250	Rockström *et al.* (1999)
beans, green	temperate	C_3	500	670	580	Rockström *et al.* (1999)
peas, green	temperate	C_3	1430	2000	1720	Rockström *et al.* (1999)
potatoes	temperate	C_3	200	400	250	Rockström *et al.* (1999)
rice	tropical	C_3			1900	Pimentel & Houser (1997)
rice	tropical	C_3	900	1400	1150	Doorenbos & Kassam (1986)
maize	tropical	C_4	940	1460	1150	Rockström *et al.* (1999)
millet	tropical	C_4	590	4370	1630	Rockström *et al.* (1999)
sorghum	tropical	C_4	1100	1800		Gleick (2000)
tropical cereals	tropical	C_4	500	2480	1400	Rockström *et al.* (1999)
sugar cane	tropical	C_4	100	200	150	Rockström *et al.* (1999)
cotton seed	tropical	C_4	2080	2230	2160	Rockström *et al.* (1999)
sunflower seed	tropical	C_4	1530	3500	2370	Rockström *et al.* (1999)
beans, dry	tropical		1730	2500	2120	Rockström *et al.* (1999)
soya beans	tropical		1250	1960	1610	Rockström *et al.* (1999)
banana, plantain	tropical		230	320	280	Rockström *et al.* (1999)
bananas	tropical		230	320	280	Rockström *et al.* (1999)
oranges	tropical		200	500	350	Rockström *et al.* (1999)

Table 3. Estimates of water for food requirements in 2050.

water for food components	consumptive water needs in 2050 ($km^3\ yr^{-1}$)
present food production:	
irrigated agriculture	1800
rain-fed agriculture	5000
eradicate current under-nourishment:	
to desired (1300 $m^3\ cap^{-1}\ yr^{-1}$)	2200
securing food for additional population 2050:	
UN medium (8.9 billion)	3600
total	12600

The blue option, increased water withdrawals for irrigation expansion and improvements of water-use efficiencies in irrigation schemes, has been thoroughly investigated, indicating a realistic contribution from irrigation of *ca.* 1000 $km^3\ yr^{-1}$ (FAO 2002). This indicates that rain-fed agriculture will have to contribute to the remaining 4800 $km^3\ yr^{-1}$, which roughly corresponds to a doubling of green water use in rain-fed agriculture over the next 50 years. This may seem high, but corresponds well with estimates that crop production will have to double over the next 30 years in order to at least keep pace with population growth (FAO 1995).

(a) *Trade-offs between water for food and nature*

The question that arises is where will this additional freshwater originate from? Basically, there are three options: (i) system trade-offs of water through land-use changes, where water use is shifted from sustaining ecological functions in other ecosystems to sustaining food production through expansion of agricultural land; (ii) water trade-offs between upstream rain-fed crop production and downstream blue water generation through increased return flow of green water to the atmosphere from rain-fed crop production; and (iii) water productivity improvements in rain-fed agriculture. As indicated above, at least 88% of present green water flow is already involved in sustaining ecological functions, indicating that every expansion of agricultural land use will most likely affect water-dependent ecological functions. The upstream–downstream trade-offs are equally sensitive to large shifts in partitioning between green and blue water flows. As suggested by de Fraiture *et al.* (2001) 40% of the accessible blue water flow (12 500 $km^3\ yr^{-1}$) needs to be safeguarded to sustain instream ecology and navigation, leaving 7500 $km^3\ yr^{-1}$ of usable blue water. However, they suggest that at least another 30% of the withdrawable water may have to be left in the river systems to avoid environmental hazards such as salt and pollutant build-up and groundwater table decline. This leaves 5250 $km^3\ yr^{-1}$ of eco-hydrologically usable blue water, which would suggest that we are already withdrawing 76% of the sustainable portion of run-off flow. Upstream–downstream trade-offs, where changes in land use upstream affect blue water flow downstream, may thus pose a very real challenge, as already is the case in several river basins in the world (e.g. Colorado River, Yellow River, Aral Sea).

In order to quantify the degree of water trade-offs that may be required between water for food and ecosystems, the focus here will be to investigate the opportunities available to improve water productivity, i.e. to generate more food with relatively less consumptive water, in rain-fed farming systems.

4. VAPOUR SHIFT: CONCEPTUAL ANALYSIS OF OPTIONS

The analysis so far on the generic nature of consumptive water needs to produce food is based on the common assumption, originating from extensive empirical observations, that there is a constant linear relationship between vapour flow and crop yield (e.g. Doorenbos & Pruitt 1992). The slope of the green water–yield line for a particular crop cultivated in a specific agro-ecological setting is the water productivity (or water-use efficiency) of that production system (commonly defined in $mm^{-1}\ kg^{-1}\ ha^{-1}$ or $m^3\ t^{-1}$). The interpretation is then generally made that the water productivity (slope of the green water and yield line) represents the consumptive water requirements over a wide yield range for a particular production system, suggesting a constant water productivity for a given crop in a specific environment.

The water productivity data in table 2 are examples of this static interpretation where, as we discussed above, the water productivity for grains on average amounts to $1500\ m^3\ t^{-1}$. This would suggest very limited options of improving water productivity. In reality, however, this static interpretation of vapour–yield relationships is strongly oversimplified. The reason is that it focuses on the entire vapour component, which includes both non-productive evaporation flow (E) (i.e. soil evaporation and interception) and productive water flow, i.e. crop transpiration (T), which directly (and linearly) contributes to yield growth. Largely, our data on water productivity originates from research conducted in the early 1950s to 1970s (Dancette 1983; Ritchie 1983; Doorenbos & Kassam 1986), during which it was difficult to separate E and T flows: and therefore these completely incompatible flows were bundled together in the awkward term evapotranspiration. It is well known, however, that evaporation and transpiration flows move in opposite directions with increased crop growth (de Wit 1958): transpiration increases linearly with crop growth while evaporation progressively declines with increased soil surface shading from a more dense crop canopy. The principle relationships between E, T and crop yield are outlined in figure 1.

Figure 1 visualizes the three principle options available to improve water productivity of consumptive water use, i.e. the ratio of consumptive water use to crop yield, by shifting the vapour relationships between E and T flow.

(i) To reduce early season soil evaporation that occurs from bare soil before full emergence of the crop (determines the intercept E_0 of the E and ET line in figure 1).
(ii) Reduction of non-productive evaporation in favour of productive transpiration as a result of increased canopy cover (determines the slope of the E line in figure 1).

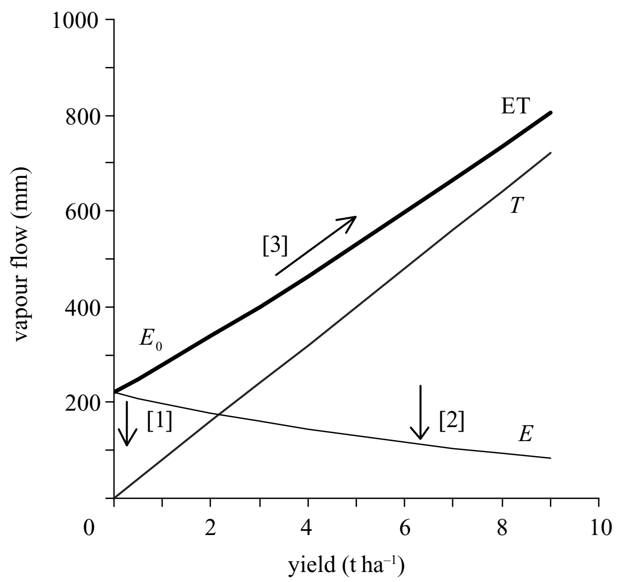

Figure 1. General relationship between crop yield and the different components of green water flow: E, non-productive green water or evaporation; T, productive green water or plant transpiration. Numbers denote vapour shift options (explained in the text), and E_0, early season evaporation.

(iii) To increase the T/ET ratio by progressively increasing yield levels through improved agricultural management (moving along the T and E lines in figure 1).

It is only vapour shift options (i) and (ii) above that constitute true 'crop per drop' improvements in absolute terms, i.e. less consumptive water is required to produce a unit crop. The third option, to improve the T/ET ratio constitutes a relative water productivity improvement, i.e. every incremental yield increase will require more consumptive water flow (due to increase in T), but the water productivity will progressively improve. Still, in terms of green water productivity, the analysis of the ratio of productive green water flow (T) to total green water use (ET flow), may be the most relevant focus in terms of assessing possibilities of 'crop per drop' improvements. First, it is difficult to significantly influence early season evaporation losses in rain-fed cropping systems. Dry planting, mulching, relay and intercropping are strategies to reduce early season evaporation by speeding up canopy development, but the effect on cumulative early season evaporation, especially in tropical savannahs, may still be relatively limited (owing to difficulties in reducing vapour pressure deficit in sparsely cultivated crop stands in dry and hot environments). Second, a focus on the relationship between total green water productivity and yield, through the ratio of T/ET flow, also encapsulates the progressive change (if any) of evaporation flow with change in yield levels. The additional water required as crop transpiration with increased crop growth can originate from two different sources: (i) a decrease in evaporation (mode [2] vapour shift), and (ii) a shift of other water flows in the water balance in favour of T (reduction in surface run-off and deep percolation affecting blue water generation).

The biophysical implication of figure 1 is that it is not possible to estimate a water productivity ratio (ET/Y) considered valid over a wide yield range based on the

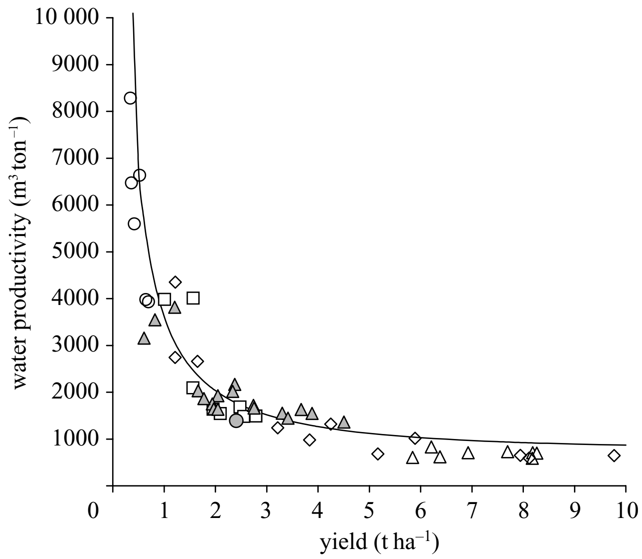

Figure 2. The dynamics of green water productivity (m^3 ton^{-1}) and yield (t ha^{-1}). The data originate from ET-flow and yield observations for different tropical grains and the line is the calibrated water productivity function in equation (4.1). Open squares, tropical grains (Dancette 1983); closed circles, maize (Alessi & Power 1976); open triangles, sorghum (Stewart *et al.* 1975); open diamonds, maize (Stewart *et al.* 1975); closed triangles, millet (Pandey *et al.* 2000); open circles, millet (Rockström *et al.* 1998). $WP_T = 800$ m^3 ton^{-1} and $b = -0.3$.

common observation of a linear ET–Y relationship from a specific cropping system. Instead, each point along the ET–Y line consists of a unique T/ET ratio, and represents a unique water productivity function of its own. Each such water productivity function reflects a certain combination of management, agro-ecology and water regime (cumulative water availability and occurrence of crop water stress during different plant development stages).

This dynamic relationship between vapour flow, yield and water productivity (WP) was analysed by Ritchie (1983), and there is ample empirical evidence in its support as seen in figure 2. Figure 2 shows green water productivity versus yield relationships for several tropical grains (sorghum, millet and maize) from different authors (Stewart *et al.* 1975; Alessi & Power 1976; Dancette 1983; Rockström *et al.* 1998; Pandey *et al.* 2000). The empirical data in figure 2 originate from different cropping systems (different crops and soils) under varying management (reflected by the spread of points for a certain crop), but similar hydro-climatic zones (semi-arid to dry sub-humid savannahs). Despite this variation in the source of data there is a general trend between water productivity and yield, which follows a natural logarithmic function. It is worth remembering that a static assumption of yield–green water relationships (where water productivity is considered by the slope of the linear relation between yield and green water flow) would result in a constant horizontal line in figure 2, crossing the y-axis at the estimated water productivity level.

The dynamic change of water productivity with increasing yields in figure 2 is a result of vapour shift (a reduction of the portion of evaporation in total green water flow) and an increase in transpiration (also contributing to a higher T/ET ratio). Musick *et al.* (1994) made similar findings for temperate dryland grains (wheat), and interpreted the curved linear relationship between water productivity and yield as a result of the green water threshold required before generating any crop yield (which according to their findings amounted to *ca.* 30% of maximum ET requirements). Based on the work by Novak (1982), who developed a simple natural logarithmic model to explain the progressive decline in E/ET with increased leaf area development, and the water-use efficiency analysis by Gregory (1988), a simple water productivity model (shown as a line in figure 2) was developed and calibrated against the empirical observations in figure 2. It should be noted that this function is not to be interpreted as a regression line with the aim of achieving the best statistical correlation, but instead it is a biophysically based function that distinguishes the two major green water components (E and T flow) and their principle influence on yield and WP dynamics. The assumption is that as transpirational water productivity is conservative, and related to the physiology and evaporative demand of the crop, total green water productivity will primarily change (with yield) as a result of a shift in vapour relationships between non-productive and total vapour flow. This can be expressed as follows:

$$WP_{ET} = \frac{WP_T}{(1 - e^{(bY)})}, \tag{4.1}$$

where WP_{ET} is green water productivity (m^3 ton^{-1}), WP_T is productive green water productivity (m^3 t^{-1}), b is a constant and Y is grain yield (t ha^{-1}). As shown by Rockström & Falkenmark (2000) WP_T is in the order of 800 m^3 ton^{-1} for tropical grains such as sorghum, maize and millet. The constant b determines the rate of decline in evaporation with increased crop canopy, and therefore also the yield level at which E/ET reaches its minimum (equal to E_0, i.e. cumulative early season evaporation in figure 1). As seen from figure 2, this minimum E/ET level, also represents the yield level above which the water productivity–yield relationship tends to fall back to a much less dynamic mode. The relatively constant WP level for higher yields in figure 2 corresponds to the constant WP normally assumed to be valid over the whole yield range. This less dynamic water productivity mode is reached at *ca.* 6–7 t ha^{-1} in figure 2, which corresponds to cropping systems with a dense canopy cover (the leaf area index exceeding 3 m^2 m^{-2}). One may speculate that this is a reason for the limited interest in analysing the dynamics of water productivity; most in-depth process research on vapour flows and yields has been carried out in temperate regions (where the E/ET ratio is low) and on cropping systems with high yield levels (i.e. close or at static water productivity mode). However, this situation (high yield, low inherent E/ET ratio) does not apply for the vast majority of farmers in the world, who instead operate at the dynamic yield range between 0.5–3 t ha^{-1}, i.e. where real water productivity gains can easily be attained.

The constant $b = -0.3$ in figure 2. In dry and hot climates with high turbulence due to sparsely cropped systems, $b > -0.3$ indicating that evaporation will remain a high portion of total green water flow when yield progressively increases, while $b < -0.3$ would represent cooler and more moist systems with denser vegetation, for example surrounded by windbreaks and agroforestry, which enable evaporation flow to rapidly decline. In a sparsely cropped system with high evaporative demand the dynamic phase would remain high over a wider yield spectrum, compared with a system where air humidity is retained within the crop stand, and thus static water productivity mode is reached at lower yield levels. Also, as WP_T will differ between different crops, and varieties of the same crop (the WP_T assumed in figure 2 is only an average for tropical grains in general), it is clear that each combination of crop and environment will in a strict sense generate its own WP–yield function. The significance of figure 2 is to demonstrate that water productivity increases dramatically with increased yield (in contrast to the common assumption of a constant relationship between WP and Y), and that the order of magnitude of this WP dynamic is relatively equal even for different crops cultivated in a similar hydro-climate.

5. VAPOUR SHIFT: IMPACT ON WATER RESOURCE MANAGEMENT

The focus in this paper is on major cereals in developing countries. It is here that almost the totality of population growth occurs, and where the dominant share of tropical agriculture is found. It is also here that the lowest yield levels are experienced (generally 1–2 t ha^{-1}) and the largest evaporation losses in the on-farm water balance (up to 50% of seasonal rainfall) (Rockström 2000). These factors indicate a large potential for vapour shift and water productivity improvements.

Average yield levels of major rain-fed cereals is currently 2 t ha^{-1}.[1] Based on recent projection on yield growth—from 2.5% between 1995 and 2030 (FAO estimate) to 1.5% between 2030 and 2050—the average grain yield level in 2050 may attain 3.5 t ha^{-1} . The cultivated area is expected to increase from 466 to 535 million ha, at a slow rate of 0.09% yr^{-1} between 1995 and 2030, and an even lower rate of 0.05% for the period 2030–2050. This will give a total cultivated area under cereals in 2050 of *ca.* 600 million ha. The production of cereals will then amount to 2100 million tons compared with 1200 million tons today, with a projected production in 2030 of 1900 million tons.

Applying the dynamic water productivity function (equation (4.1) and figure 2) can give us an indication of the 'crop per drop' implications of such a yield increase, which in turn can be used to re-assess the projections of water for food requirements in table 3 (which indicated an additional water need in rain-fed agriculture of 4800 $km^3\,yr^{-1}$ in 2050). Present tropical farming systems (average yield, 2 t ha^{-1}) operate at a WP of 1800 $m^3\,ton^{-1}$ (200 mm $t^{-1}\,ha^{-1}$), while the yield increase to 3.5 t ha^{-1} would result in an improved WP of 1200 $m^3\,ton^{-1}$, indicating a 'water saving' compared with a static approach to water for food estimates of 600 $m^3\,ton^{-1}$. Applying this dynamic improvement in WP to the 600 million ha of tropical grains in developing countries, would result in a relative 'crop per drop' saving of 500 $km^3\,yr^{-1}$. This is a substantial reduction in water for food requirements, which even though it 'only' amounts to *ca.* 10% of estimated total additional water needs for rain-fed agriculture, corresponds to 25% of present blue water withdrawals for agriculture.

6. VAPOUR SHIFT: OPTIONS AVAILABLE TO THE FARMER

What are the realistic options for smallholder farmers in rain-fed tropical farming systems to increase yield levels of staple food crops and simultaneously improve water productivity in line with figure 2? This question is critical particularly in savannah farming systems, where rain-fed farming is practiced in inherently vulnerable ecosystems, subject to recurrent water scarcity and serious human land degradation. As shown by Rockström & Falkenmark (2000) there is a large yield gap in savannah agro-ecosystems, between farmers' yields (0.5–3 t ha^{-1}) and achievable yields (4–6 t ha^{-1}) within the same agro-ecological setting. This yield gap is strongly related to management and human-induced land degradation, and indicates a large potential of improving yield levels.

(a) *Bio-physical deficiencies*

Bio-physical determinants of crop yields can be divided according to three agro-hydrological deficiencies that contribute to yield reductions (Rockström & Falkenmark 2000; table 4). Hydro-climatic deficiencies are partly unmanageable in rain-fed agriculture (meteorological droughts) and partly manageable (dry spell mitigation). Soil and crop deficiencies are in general manageable.

Hydro-climatic deficiencies set the boundary conditions of potential yields and are manifested as low cumulative rain, meteorological droughts and dry spells. Soil deficiencies are manifested by low soil infiltrability and poor water-holding capacity of the soil. Plant deficiencies are manifested by poor plant water uptake capacity, due to weakly developed roots and canopies, in turn related to for example compaction and soil nutrient deficiencies.

(b) *Management options*

In order to improve water productivity, the aim is to reduce the bio-physical deficiencies in table 4 by maximizing on two agro-hydrological factors.

(i) Crop water availability (by maximizing rainfall infiltration and soil water-holding capacity).
(ii) Crop water uptake capacity (by maximizing canopy cover, root density and root depth).

Both these water-related factors will affect green water productivity by shifting vapour in favour of an increased *T*/ET ratio. However, the means to achieve improvements in (i) and (ii) are not necessarily through water management alone but instead through integrated approaches that simultaneously improve plant nutrient access, timing of operations, pest management, cropping system, tillage practices, etc. Management options that can improve yields and shift vapour in favour of increased water productivity are shown in table 5 for smallholder rain-fed farming in savannah environments.

(c) *Evidence of water productivity improvements through dry spell mitigation*

A major challenge in savannah agro-ecosystems is the frequent occurrence of dry spells and droughts caused by

Table 4. Biophysical deficiencies affecting yield levels.

biophysical deficiency	factors	manifestation	hydrological impact	management
hydro-climatic deficiency	seasonal rainfall rainfall variability in space and time evaporative demand	extreme meteorological events droughts, floods, dry spell	low plant available soil moisture	soil and water management
soil deficiency	soil texture soil structure root depth slope soil chemical properties	soil crusting soil compaction low water-holding capacity low fertile soils contaminated soil	low plant water uptake capacity	tillage biological soil management
plant deficiency	soil-nutrient availability crop pests and disease	weak roots poorly developed canopy	low plant water uptake capacity	crop management

Table 5. Management strategies to improve green water productivity.

water productivity strategy	process (refers to figure 1)	management options	effect
real vapour shift	[1] reduce early season evaporation	dry planting	quick crop establishment
		mulching	reduced evaporation flow
		zero tillage	less soil exposure to the atmosphere
		intercropping	maximize canopy cover
	[2] reduce evaporation flux with increased canopy	intercropping	maximize canopy cover
		mulching	
		windbreaks	reduced energy inflow through advection
		agro forestry	reduced energy inflow through advection
relative vapour shift improved T/ET ratio	[3] increase plant water uptake maximize productive green water flow	improved crop varieties	
		water harvesting	dry spell mitigaton
		soil and water conservation	maximize infiltration and WHC
		soil fertility management	maximize plant water uptake
		conservation tillage	maximize infiltration, WHC and rooting depth
		intercropping	maximize transpiration

highly unreliable rain-fed distribution, high evaporative demand, and high intensity of rainfall. The result is a high risk of yield failure due to water scarcity, but not necessarily due to absolute lack of water, but due to poor distribution of water availability over time. The implication is that even though water is not always the major limiting factor for crop growth, it forms an important entry point in efforts of improving agricultural productivity. As shown by Barron *et al.* (2003), dry spells—short two-to-four-week periods of crop water stress—in semi-arid savannah agro-ecosystems are very common, often occurring each rainy season. Mitigating dry spells through different forms of water harvesting, where run-off is collected and used for supplemental irrigation during short dry spells, can contribute to increase yields and water productivity. Figure 3 shows results from on-farm research on small water harvesting systems for supplemental irrigation of sorghum in Burkina Faso (black points) and maize in Kenya (white points) cultivated under semi-arid conditions in locations with annual rainfall ranging from 550–750 mm (bi-modal in the Kenyan location) (Barron *et al.* 1999; Fox & Rockström 2000). Supplemental irrigation of 60–80 mm per season was applied from small open farm ponds (150–300 m^3 storage capacity) collecting sheet, rill and small gully run-off flow from upstream degraded land areas (grazing land and foot paths). Supplemental irrigation (denoted 'water' in figure 3) was combined with fertilizer application (denoted 'nutrient' in figure 3). Fertilizer application was applied at a low rate of 30–50 kg N ha^{-1} and 15 kg P ha^{-1} (with one combination of N of 80 kg ha^{-1} in the Kenyan case). The effect on yield and water productivity of integrating water and soil nutrient management are also shown (denoted 'water and nutrients' in figure 3). Each point in figure 3 represents an average of 3 years' data (1998–2000) for each treatment combination. Details on experimental set-up and research methodologies are found in Fox & Rockström (2000) and Barron *et al.* (1999). Water productivity from observed data are calculated for total water supplied to the crop (i.e. m^3 of rainfall + irrigation per ton of grain yield). For reference purpose, the line in figure 3 shows the corresponding green water productivity function presented in figure 2.

As seen from figure 3 soil nutrient management and supplemental irrigation results in a combined increase in both yield levels and water productivity. Dry spell mitigation and increase in crop nutrient access improves both plant water availability and water uptake capacity,

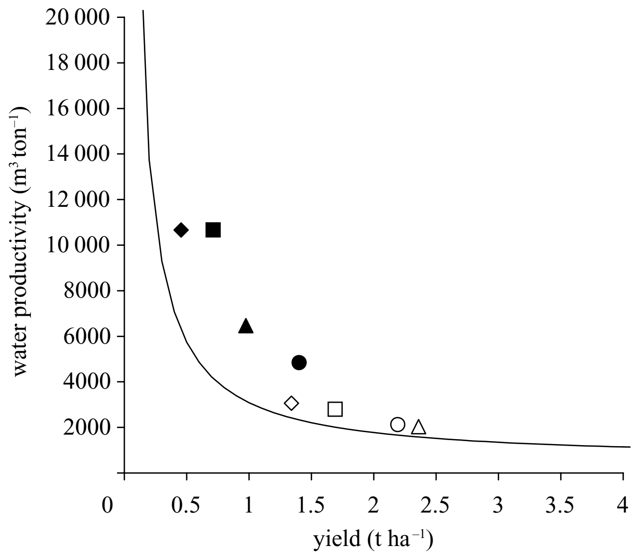

Figure 3. The effect of soil and water management on water productivity. Points show total water productivity (rainfall + supplemental irrigation). Black points show data on sorghum from Burkina Faso and white points show data on maize from Kenya (Barron *et al.* 1999; Fox & Rockström 2000). The line shows green water productivity estimated from equation (4.1). Diamonds, control; triangles, nutrients; circles, water and nutrients; squares, water.

resulting in increased yields and a vapour shift in favour of productive green water flow (indicated by the green water productivity function in figure 3). The sorghum system in Burkina Faso currently experiences very low present yield levels (control yield of 0.5 t ha^{-1} on average) and is practiced in a hot semi-arid savannah environment with very high evaporative demand (more than 5 mm d^{-1}). In this agro-hydrological setting, the yield improvements through integrated soil and water management, which increased yield levels by a factor of three (from 0.45–1.4 t ha^{-1}) resulted in a reduced rainwater need of 5800 m^3 ton^{-1} (the corresponding green water saving following the function from equation (4.1) would be a relative reduction in green water requirements with 4000 m^3 ton^{-1}). This farming system is thus operating at the dynamic end of the water productivity function (low yield and high evaporation losses). In the Kenyan case, for maize cultivated on more fertile soil with lower evaporative demand (less than 5 mm d^{-1}) and slightly higher rainfall, the yield increased, on average, a factor of 1.6 (from 1.3–2.2 t ha^{-1}), with a relative rainwater saving of 900 m^3 ton^{-1} (or 800 m^3 ton^{-1} for green water according to equation (4.1)).

(d) *Replicating win–win solutions*

While there is limited data on water productivity implications of water harvesting systems for dry spell mitigation, there is ample evidence of yield improvement using various techniques of soil and water conservation (Liniger 1997) and water harvesting (Sivannapan 1995; SIWI 2001). An important area receiving increased attention in tropical agriculture is conservation farming, where conventional tillage based on soil inversion is abandoned in favour of non-inversion tillage (e.g. ripping and subsoiling) and zero tillage systems. These are important developments, as it has been shown that conventional ploughing in tropical environments contributes to land degradation through compaction, wind and water erosion, and rapid combustion of soil organic matter (Benites *et al.* 1998). These factors have negative effects on water productivity and yield levels. The negative impact on ecosystems are double; first, large volumes of non-productive vapour flow are 'lost' resulting in larger volumes of water required to produce one unit of food, and second, poor land management results in land degradation that (i) increases sediment and nutrient flow into downstream ecosystems (such as wetlands and lakes), and (ii) increases the pressure to expand agriculture into natural ecosystems due to low productivity on existing farm land. As shown by Hobbs & Gupta (2003) and Rockström & Steiner (2003), there are large water productivity gains and yield improvements to be made through the integrated adoption of non-inversion farming practices.

In a global review of indigenous and appropriate management options for upgrading rain-fed smallholder farming systems in the tropics, Pretty & Hine (2001) showed that there are large opportunities of sustainable yield improvements (on average 50–100% yield increases compared with 5–10% yield increases in irrigated cropping systems). These examples, despite being successes generally attained only at a local scale, show the possibilities of influencing water for food requirements, water and land trade-offs with other ecosystems, and food security, through management even in inherently vulnerable agroecosystems subject to water scarcity.

7. CONCLUSIONS AND DISCUSSION

It is argued in this paper that the challenge of sustainable freshwater management is strongly linked to securing water for food for a global population of approximately nine billion people in 2050. No sector of direct human water dependence uses so much freshwater, and no land use affects trade-offs between different functions of water in nature, as does agriculture. Furthermore, widening the freshwater approach, to an eco-hydrological approach, clearly shows that the water for food challenge must be addressed both in the blue water-using sector—irrigation—and in rain-fed agriculture, which depends on direct rainfall infiltration and the return flow of green water to the atmosphere. The trade-offs between water for food and nature become apparent when all water-dependent ecological functions are analysed. As shown, estimates suggest that 90% of present green water flows are involved in generating biomass-related ecosystem goods and services. Preliminary assessments further suggest that almost 80% of sustainably usable blue water resources are already withdrawn for direct human use (*ca.* 4000 km^3 yr^{-1} at present of a sustainable ceiling of 5250 km^3 yr^{-1}). It thus seems clear that feeding tomorrow's world will imply water trade-offs between different water-dependent ecological functions.

Based on regional diets and crop water requirements present water for food needs were estimated at 1200 m^3 cap^{-1} yr^{-1}, with a desired volume of 1300 m^3 cap^{-1} yr^{-1} in order to reduce under-nourishment in developing countries. This translates to a global water for food requirement of 12 600 $km^3\ yr^{-1}$ in 2050. The human water for food demands were also shown to be generic for different hydro-climates in the world, in the sense that the water productivities for major grains do not present large differences, whether grown in temperate or tropical regions. This generic approach, which is based on the conventional static assumption of a linear relationship between consumptive crop water use and crop yields, is in sharp contrast to the dynamic water productivity relationship presented in figure 2 and equation (4.1). Basically, the dynamic analysis suggests that the water needs to generate a certain diet are directly related to the yield levels in the farming systems producing the food, and that the water volumes differ dramatically depending on agricultural management. Therefore, while the generic water for food estimates may be of use in general assessments of freshwater use at national and regional scales, it is important to keep in mind the dynamic nature of water productivity at the local farm level.

As shown from the dynamic water productivity analysis, increasing agricultural productivity through improved management may result in relative water savings in the order of 500 $km^3\ yr^{-1}$ in rain-fed farming systems in tropical environments characterized by water scarcity. Even though this is a significant reduction in agricultural water use, there still remains an estimated deficit in rain-fed agriculture of 4300 $km^3\ yr^{-1}$ in 2050. This poses a major challenge for sustainable freshwater management, as it implies large-scale land-use changes, where freshwater use is shifted from water-dependent ecosystems to rain-fed cropland. However, it is important to note that several factors may affect the size of the rain-fed water for food challenge. To start with, while the global water for food needs in 2050 are truly global, the analysis on water productivity gains are focused on water-scarce tropical environments. Despite the rationale for doing this—that the largest relative water productivity improvements may be achieved here and that it is in the savannah zone that water scarcity pose the largest eco-hydrological and socio-economic constraints—the fact remains that water productivity gains obviously can be achieved in the arid and humid tropical zones, as well as in the temperate zone. Also, even though the dynamic water productivity analysis is based on an optimistic outlook of the possibilities of producing more 'crop per drop', and while the irrigated contribution to future food production is similarly taken from optimistic projections based on expectations of large irrigation efficiency improvements, there is still room for divergences from the estimated water allocation to rain-fed agriculture given in this paper. Plant breeding, biotechnology and new crop systems (such as aerobic rice) may strongly influence water productivity levels. In this sense, the present analysis, while capturing the WP dynamics at low yield levels, may not adequately have captured the opportunities of WP dynamics at the higher yield range (as a result, for example of higher harvest indexes and drought tolerant crop varieties). Similarly, present irrigation water efficiencies are low, generally with less than 50% of water withdrawals contributing to consumptive crop water use. Systems such as drip irrigation, which increasingly are available and affordable to smallholder farmers, enable irrigation efficiencies of 90% (i.e. only 10% of applied water does not contribute to green water flow), which means that the potential contribution of food and 'crop per drop' improvements in irrigation may be higher than assumed in this paper. Certainly, the food challenge facing mankind, and the potential water crisis following in its path, is of such a magnitude that all efforts need to be made in both irrigated and rain-fed agriculture in order to maximize food output and water productivity.

Furthermore, another option, which has not been raised in this paper, is to reorientate the consumptive water use from environments where the trade-off would have severe environmental effects (as in water-scarcity-prone ecosystems) to water-rich regions of the world, where there is surplus water. This virtual water option (Allan 1995) is favoured among economists, as it conforms with the notion of producing food where the comparative (water) advantage of doing so is largest. Food trade driven by water scarcity is already occurring at large scale. Postel (1998) suggests that 25% of the present grain trade is driven by water scarcity, i.e. 'virtual water' in the form of grain is imported to water-scarce regions. However, this virtual water trade is concentrated in arid countries with high purchasing power (e.g. oil-rich countries in the Middle East). By contrast, the regions of the world experiencing the fastest population growth and highest level of under-nourishment are also the regions with a high portion of rural inhabitants with low purchasing power and low alternative sources of livelihood. This would suggest that maximizing food production at the doorstep of the rural poor will remain a major challenge in the future. The opportunities of gaining benefits not only in terms of food security and poverty reduction, but also in terms of water productivity and environmental management, may constitute additional justifications for increased attention to rain-fed agriculture in vulnerable environments. However, it does seem clear that the magnitude of productivity gains required in order to secure food for rapidly growing populations in rural poverty stricken countries are so large that no less than a new Green Revolution is required. Within this context, an important component of integrated water resource management is how to wisely balance the large increased water needs in agriculture—which seem unavoidable despite water productivity improvements—with other water-dependent human and ecological uses of freshwater.

This paper builds on results from collaborative research between Unesco-IHE and the Department of Systems Ecology, Stockholm University in Sweden. Professor Malin Falkenmark, Professor Carl Folke and Ms Line Gordon contributed to the conceptual development and analyses of green and blue water flows with a focus on terrestrial ecosystems. The field research data on water harvesting for dry spell mitigation originates from the research by Dr Patrick Fox (Burkina Faso) and Mrs Jennie Barron (Kenya), which is funded by Sida/Sarec, Sweden.

ENDNOTE

[1]Including rice (3.7 $t\ ha^{-1}$) wheat (2.63 $t\ ha^{-1}$), maize (2.77 $t\ ha^{-1}$), sorghum (1.04 $t\ ha^{-1}$), and millet (0.7 $t\ ha^{-1}$) (FAO 2002).

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GLOSSARY

ET: evapotranspiration
FAO: United Nations Food and Agricultural Organization
PET: potential evapotranspiration
UN: United Nations
WHC: water-holding capacity of soil