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Opportunities to increase water productivity in agriculture with special reference to Africa and South Asia

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OPPORTUNITIES TO INCREASE WATER PRODUCTIVITY IN AGRICULTURE WITH SPECIAL REFERENCE TO AFRICA AND SOUTH ASIA

A report prepared by Stockholm Environment Institute, for the Swedish Ministry of Environment presentation at CSD 16, New York 14 May 2009

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Cover Photo: © Djimengué Nanasta/ENDA

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KEY MESSAGES

- **Water productivity improvements can effectively address food insecurity and poverty alleviation**. There is a large potential to improve water productivity through improved and known water management practices. Globally, the water requirement to feed the world in 2050 would be an increase of ~4500 km^3/yr from the current ~7000 km^3/yr. Our estimates suggest that water productivity improvements could save up to 2200 km^3/yr reducing the future additional needs to ~2300 km^3/yr. This saving is larger than the world's current total consumption of water in irrigated agriculture.

- **Management practices that increase agricultural yields also improve water productivity**. There is a true win-win opportunity to produce more crop-per-drop of water. This is primarily achieved by reducing water losses on the farmer's field. A key starting point for increasing yields is to ensure that adequate water is available for crop growth.

- **The greatest potential to increase yields and water productivity is in areas where agricultural productivity is currently low**. Such areas include low input rainfed agriculture in Sub-Saharan Africa and South Asia, which provides the food for most of the poorest in the world, in regions where water resources often are considered scarce and where future water demands for food grow fastest due to population growth and development needs.

- **Major opportunities to improve water productivity are found in water management practices along the continuum from rainfed to partially and fully irrigated farming systems.** The key is to integrate non-structural and structural measures and investments targeted at crop management, soil and water conservation, and irrigation practices.

- **Water productivity gains are realised also by non-water management interventions**. These measures include the choice of crop varieties, fertilizer investment, pest and weed management, timely operations and post harvest management

- **Improving livestock water productivity should be an integral part of water resource management**. Livestock provide livelihood support and a store of wealth for many of the world's poor. The water requirements of livestock and efforts to improve water productivity in the sector in concert efforts to improve crop water productivity.

- **Water productivity gains in agriculture can secure water resources for other landscape uses and ecosystem services**. There is a need to widen the perspectives on water management from farm level to watershed level, and to integrate land use related water demands in resource negotiations and priority settings.

- **Integrated water and land management at the watershed scale is the key to improving water productivity and enabling sustainable water resource management**. Tapping the opportunity of improved water productivity will require an integrated management of green and blue water resources, which in turn will require a downscaling of the focus of IWRM from the river basin to the watershed level. The challenge for IWRM is to manage trade-offs when re-allocating green and blue water across scales from field to watershed level, and to limit negative side-effects such as reductions in downstream water availability due to upstream land management activities.

- **Targeted policy actions can support integrated water and land management for improved water productivity.** Policies need to address constraints in the adoption of good soil and water management practices such as insufficient human capital, labour, and affordable access to land, credits, high-quality seeds, fertilizers, pesticides and markets.

- **Capacity building and awareness are essential**. Knowledge exists, but human capacity, knowledge transfer and awareness raising are essential to manage simultaneously the complexity of water and land management for water productivity gains, sustainable development and poverty alleviation. A particular opportunity exists in training a new generation of water resource planners and managers of both green and blue water resources at the watershed level.

INTRODUCTION

The world is facing an impending water shortage that will complicate national and global efforts to alleviate and prevent food shortages in many regions. Food production is the world's second largest water consuming economic activity (surpassed only by another biomass producing sector, forestry). An adequate human diet takes about 4000 liters of water per day to produce, which is over 90 per cent of the daily human water requirement. Given these facts, solving the problems arising from water scarcity in agriculture is an urgent matter. Business as usual is no longer an option. The increasing water scarcity resulting from population growth, rising incomes, and climate change, limits the amount of water available for food production and threatens food security in many countries. As the world's population grows and incomes rise, farmers will – if they use today's methods – need a great deal more water to keep everyone fed: another 1600 km^3/yr just to achieve the UN Millennium Development Goals of halving hunger by 2015 (SEI, 2005), and another 4500 km^3/yr with current water productivity levels in agriculture to feed the world in 2050 (Falkenmark *et al*., 2009; Rockström *et al*., 2009) This is more than twice the current consumptive water use in irrigation, which already contributes to depleting several large rivers before they reach the ocean. It is becoming increasingly difficult, on social, economic and environmental grounds, to supply more water to farmers.

Increasing crop water productivity is a key response option where water is scarce compared with land and other resources involved in production. Improvements to agricultural water productivity (water productivity in crop, livestock and aquaculture production) help to meet rising demands for food from a growing, wealthier, and increasingly urbanized population, when at the same time there are pressures to reallocate water from agriculture to cities and to make more water available for environmental uses contribute to the urgency for achieving gains in agricultural water management. There is a clear link between water, poverty reduction and economic growth (e.g., ADB, 2005). For the rural poor more productive use of water can mean better nutrition for families, more income, and productive employment (Molden *et al*., 2009).

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As we discuss in this report, many regions in the world need not face a water crisis ifwater resources are managed wisely and efficiently. Part of the solution to the apparent water crisis will be found in how water is developed and managed, especially in agriculture,. For historical reasons the individual sectors, such as agriculture, human settlements and industry, usually manage water independently of each other. In future, water must be managed in a coordinated way, despite the fact that its different uses often appear to be unrelated. As the strong interrelations of the activities of upstream and downstream users illustrate, water is a unitary resource and should be managed accordingly (Lenton and Muller, 2009). The concept of water productivity can be used to manage water flows from farmers crops and livestock to the wider demands for water in the landscape.

Water scarcity is a relative concept and there are various indicators and thresholds of water scarcity. Although the global amount of renewable fresh water has not changed, the amount available per person is much less than it was in 1950, due to population growth and increasing demands on available resources. Water is not equally distributed throughout the world and impacts of climate change will vary among regions.

Our primary goal in this paper is to describe how improvements in water and land management can increase the productivity of water in agriculture, which, broadly defined, means getting more value or benefit from the volume of water used to produce crops, fish, forests and livestock (Kijne *et al*., 2003). We begin by reviewing water scarcity and water productivity at the global level. We then describe ten Key Messages regarding efforts to improve water productivity in agriculture, with emphasis on Africa and South Asia.

WATER SCARCITY: WHERE ARE WE FACING A WATER CRISIS?

Water scarcity is a relative concept. Using the conventional approach and assessing the amount of renewable surface and groundwater per capita (i.e.so called blue water), suggest that water stress is increasing in a number of countries and regions are moving into increasing water stressed conditions. Although the global amount of fresh water has not changed, the amount available per person is much less than it was in 1950, with a significant difference between countries and regions. Water is not equally scarce in all parts of the world. As Figure 1a illustrates, South, East Asia and the Middle East/ North Africa region are the worst affected in terms of blue water scarcity. However, this picture may be misleading because the average amount of water per capita in each pixel could obscure large differences in actual access to a reliable water source. In addition, these water quantities only include blue water. The full resource of rainfall, and notably "green water", i.e., soil moisture used in rainfed cropping and natural vegetation, is not included. In a recent assessment that includes both green and blue water resources, the level of water scarcity changes significantly for many countries (Figure 1b).

Among the regions that are conventionally (blue) water scarce, but still have sufficient green and blue water to meet the water demand for food production are large parts of sub-Saharan Africa, India and China. If green water (on current agricultural land) for food production is included, per-capita water availability in countries such as Uganda, Ethiopia, Eritrea, Morocco and Algeria more than doubles or triples. Moreover, low ratios of transpiration to evapotranspiration (T/ ET) in countries such as Bangladesh, Pakistan, India and China indicate high potential for increasing water productivity through vapour shift (Rockström *et al*., 2009).

Absolute water stress is found most notably in arid and semi-arid regions with high population densities such as parts of India, China and the North Africa /Middle East (MENA) region. The MENA region is increasingly unable to produce the food required locally due to increasing water stress from a combination of population increase, economic development and climate change, and will have to rely more and more on food (and virtual water) imports.

For the greater part of the world the global assessment of green and blue water suggests that water stress is primarily a blue water issue, and large opportunities are still possible in the management of rainfed areas, i.e., the green water resources in the landscape (Rockström *et al*, 2009). The current global population that has blue water stress is estimated to be 3.17 billion, expected to reach 6.5 billion in 2050. If both green and blue water are considered, the number currently experiencing absolute water stress is a fraction of this (0.27 billion), and will only marginally exceed todays' blue water stressed

What is water productivity and why is it important?

Water productivity is a measure of the amount of water needed to generate an amount (or value) of produce. Because water productivity can be quantified it enables improvements to be charted, thereby encouraging faster progress (Passioura, 2006). Some commentators disagree with the use of the term 'productivity' in this context and prefer to use it only for the classical production factors of labor, land and capital (Zoebl, 2006). Indeed, irrigation efficiency and water use efficiency are still useful parameters provided they are well defined and used at the level of individual farmers or irrigation projects. 'Water productivity' can be quantified at higher scales, but its meaningful use is also conditional on unambiguous definitions.

The main reason to improve agricultural water productivity (water productivity in crop, livestock and aquaculture production) is to meet rising demands for food from a growing, wealthier, and increasingly urbanized population, while there are pressures to reallocate water from agriculture to cities and to make more water available for environmental uses. An additional reason derives from the link between poverty reduction and economic growth. For the rural poor, more productive use of water can mean better nutrition for families, more income, and productive employment (Molden *et al*., 2009).

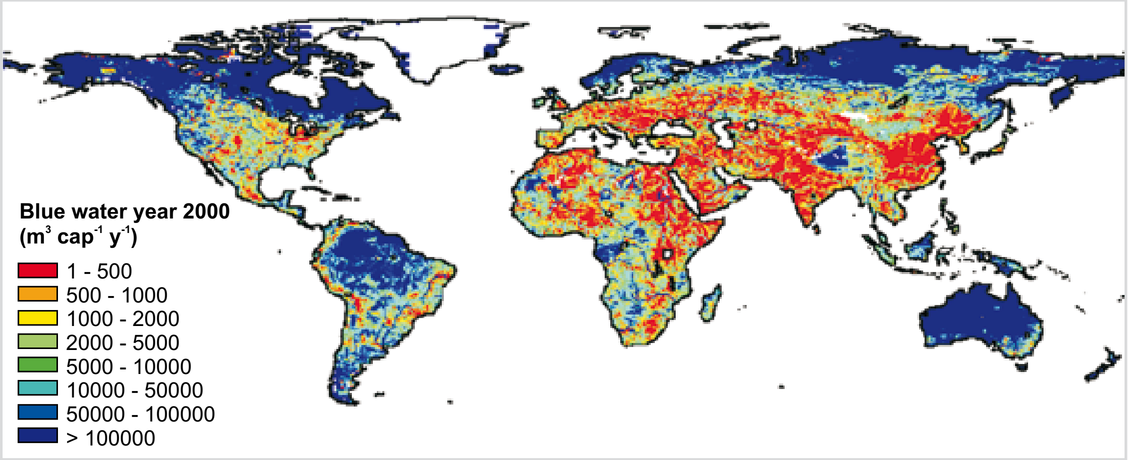


Figure 1a: Renewable liquid freshwater (Blue) water stress per capita (m^3 cap^{-1} a^{-1}) using LPJ dynamic modeling year 2000

(After Rockström *et al*, 2009)

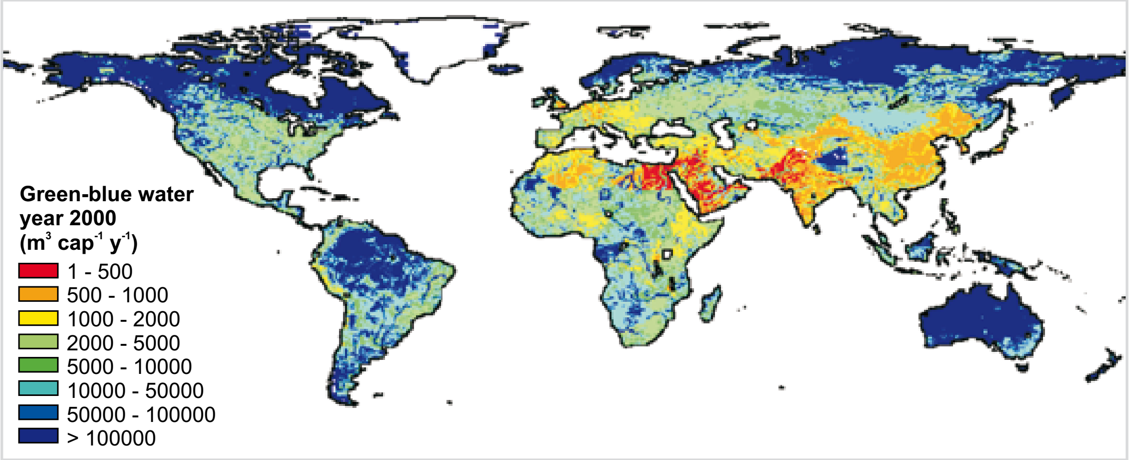


Figure 1b: Renewable rainfall (green and blue) water stress per capita (m^3 cap^{-1} a^{-1}) using LPJ dynamic modeling year 2000

population by 2050 when it is expected to reach 3.97 billion (Figure 2).

We conclude that a water resource assessment including both green and blue water offers new opportunities in water management. When both green and blue water are included in the assessment, the risk of water scarcity is still evident, but the opportunities to address it also become clear. They largely lie in the area of land management, to improve green water productivity in addition to conventional blue water management.

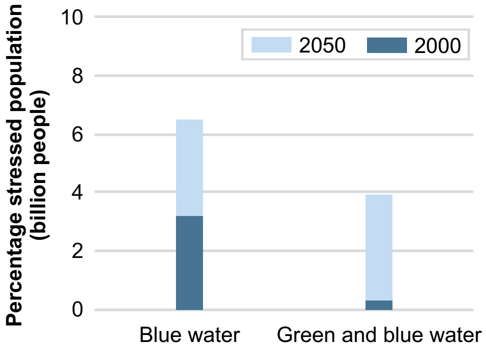


Figure 2: Population living in blue water stress (absolute water scarcity) and green and blue water stress in 2000 and 2050

(After Rockström *et al*, 2009)

WATER PRODUCTIVITY AT THE GLOBAL SCALE

Attempts to raise crop water productivity show most promise in areas where water productivity is low, but where green water is still untapped (cf. Fig, 1a and b). Those areas often coincide with high incidence of poverty (Molden *et al*., 2009). Additional opportunities lie in areas where (blue) water resources have not been fully developed. These opportunities can mostly be addressed with additional investments in infrastructure.

On a global scale, water productivity for cereals can be estimated using current yield levels (Figure 3). It is clear that certain regions, sub-Sahara Africa, Australia and parts of Asia have, at the global to national scale, large scope for improving water productivity in crop production. It is also evident, that many nations with low water productivity also have low incomes and high poverty incidence (apart from Australia) (cf. Dixon *et al*. 2001). This implies that a focus on these areas can both reduce the amount of additional water needed for agriculture globally and help to reduce poverty locally.

When comparing global/national water productivity in Figure 3 with green-blue water stress levels at the global scale (Figure 1b), it is also evident that there are significant additional areas where green water is available, and water productivity can be improved significantly, particularly in sub-Sahara Africa.

In arid and semi-arid regions, water availability is often a key limiting input. In such situations, where water availability is the binding constraint that limits agricultural output, producers should seek to optimize water productivity. This can be achieved by modifying water management practices, and by improving the use of other inputs that contribute to agricultural production. Concepts embedded in the notion of integrated resource management are pertinent in this discussion, as water is combined with many other inputs, and the best production strategy often will require optimisation of several inputs at one time, or within one production season.

In many highly productive regions, crop water productivity is already quite high and gains in yield (per unit of land area) do not necessarily translate into further water productivity gains. Some observers perceive that low water use efficiencies on irrigated fields indicate opportunities for improving water productivity. However, reuse of water that takes place within an irrigated area or basin often compensates for the losses at field level, even though water quality often suffers during reuse.

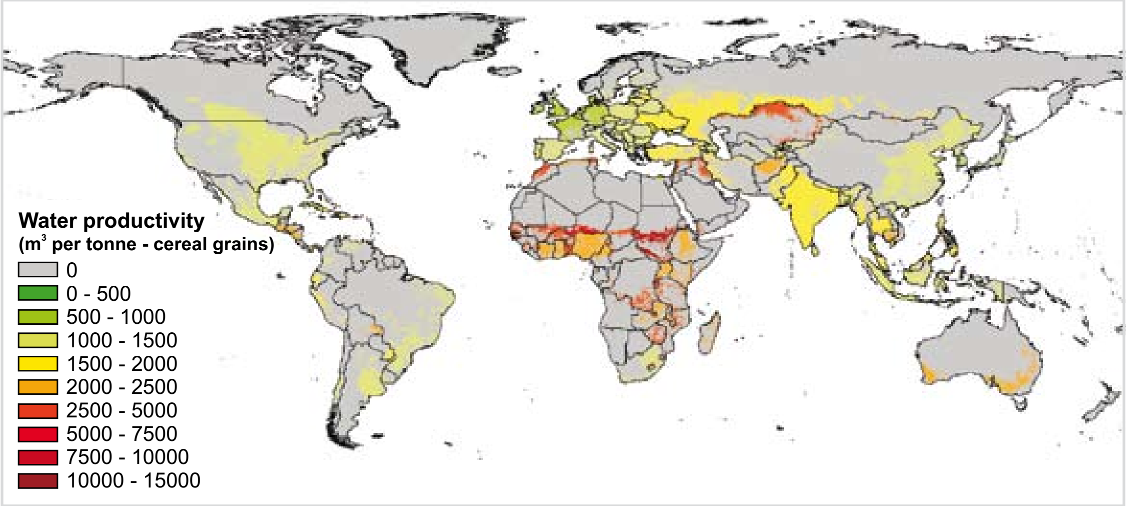


Figure 3: Water productivity for cereals (m^3 per to grain produced)

(Data from FAOStat (2009), and personal communication Zwart, 2009)

MESSAGE 1: WATER PRODUCTIVITY IMPROVEMENTS CAN EFFECTIVELY ADDRESS FOOD INSECURITY AND POVERTY ALLEVIATION

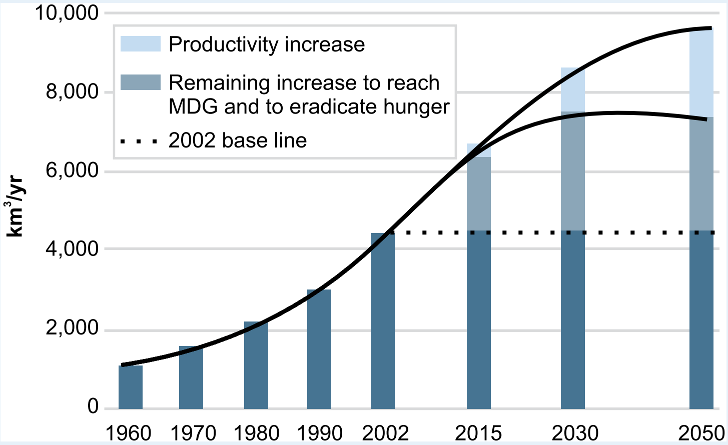
Given the increasing pressures on water resources and the increasing demands for food and fiber, the world must succeed in producing more food with less water (Box). Hence it is essential to increase water productivity in both humid and arid regions. Some describe the goal as increasing the "crop per drop" or the "dollars per drop" produced in agriculture. Regardless of the metric, it is essential to increase the productivity of water and other inputs in agriculture. Success will generate greater agricultural output, while also enabling greater use of water in other sectors and in efforts to enhance the environment.

Water productivity can vary with household income, as farmers' yields vary as a result of local input and management styles. In a household level study of 300 farmers in eight sub Saharan countries, the more wealthy farmers had generally higher yield levels (Holmen, 2004), and subsequently better water productivity (Figure 4). The differences were significant between the wealthier classes and poorest classes. More than 1,000 m^3 additional water was required per ton of maize grain produced by the poorest farmers compared to the wealthiest farmers. Data suggest that yield improvements for the purpose of poverty alleviation can also significantly improve water productivity, especially in current low yielding rainfed (green water) agriculture, in sub Saharan Africa and parts of South Asia.

Water productivity improvements are important to attain the Millennium Development Goal on hunger (MDG 1)

The Millennium Development Goals presents a formidable challenge, not least in realizing the target to halve hunger by 2015. To produce more food in the developing world, more water needs to be appropriated for crop and livestock. Assuming a balanced dietary consumption requiring 1,300 m^3 cap^{-1} y^{-1}, an additional 2,200 m^3 y^{-1} is needed to achieve the MDG1 target on hunger by 2015. To eradicate undernourishment by 2030 corresponds to 4,200 m^3 y^{-1}, reaching 5,200 m^3 y^{-1} by 2050 for additional water for crop and livestock production.

Water productivity improvements are essential to reduce pressure on water resources. If we assume improved water productivity from 1,800 m^3 to 1,200 m^3 per ton of grain produced, the corresponding required water for meeting MDG by 2015 is still a considerable additional water demand. The estimated additional water requirements, allowing for water productivity improvements, are of the order of 1,850 m^3 y^{-1} in 2015, to about 3,000 m^3 y^{-1} in 2030, and in 2050. This additional requirement presents a great challenge, when we also consider the need to allocate water resources for other things than agricultural production.



After SEI (2005): Sustainable Pathways to attaining the Millennium Development Goals

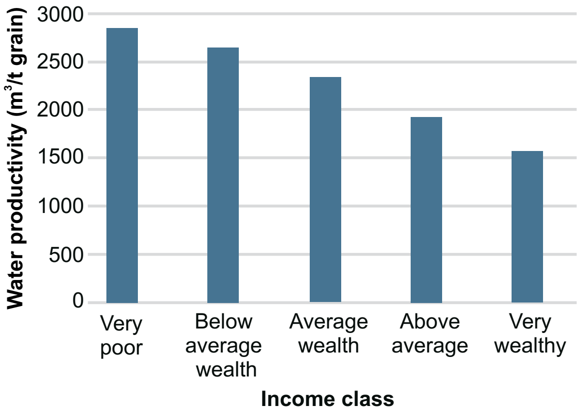
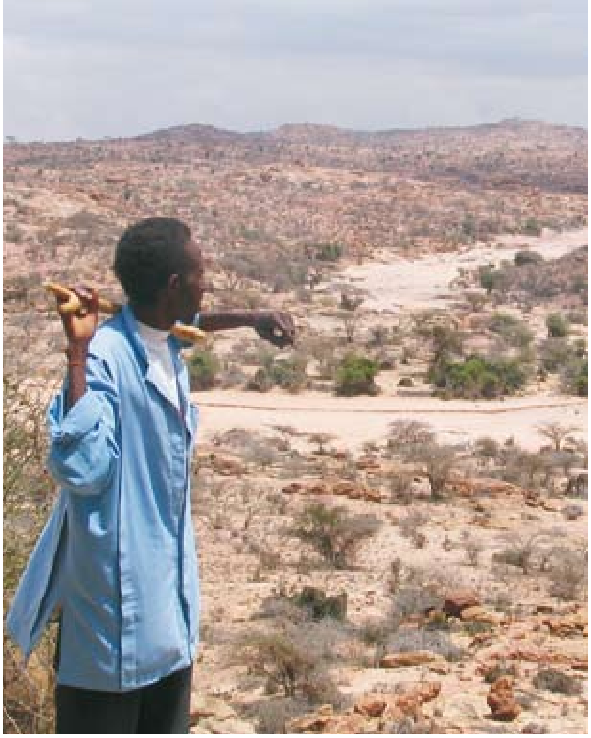


Figure 4: Water productivity for maize yields and income levels for smallholder farming systems in sub-Sahara Africa (based on Holmen, 2004)

Most of the poor in developing countries live in rural areas and rely on agriculture for their livelihoods. Many poor also live in cities, where they must purchase food at prices determined largely within local markets. Successful efforts to increase water productivity and production can improve food security and reduce poverty in both rural and urban areas. In rural areas, farmers have opportunities to produce more food with their available land and water resources. In subsistence settings, this will enable farmers to increase the amount of food available for their households. In market settings, farmers have opportunities to sell additional produce, thus increasing their annual income. The extent to which poverty is reduced will depend on the ability of farmers to access markets and the proportion of market revenue they will retain. In addition, the revenue they retain must exceed the costs they incur in producing higher yields and transporting the additional produce to market.



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Higher crop water productivity can also improve incomes in rural areas through an employment effect. If all else is equal, the incremental value of labor will increase when crop water productivity increases. At the margin, this will cause an increase in the demand for farm labor. In some settings, farmers will require more labor for production, harvesting, and transport of their produce to markets. Additional labor might also be needed in the processing and marketing of some crops. Households providing the labor will gain revenue that might enable them to improve their food security and lift them out of poverty over time.

In summary, the impacts of improvements in crop water productivity on food security and poverty reduction will depend on several economic and institutional parameters that determine how those impacts are transmitted at the household level. Generally, increases in agricultural productivity will result in higher crop production levels with available resources. Thus farm and non-farm households might benefit from lower food prices and increased employment opportunities. The degree of success in improving food security and reducing poverty will vary between regions with differences in the increased costs of production, the ability of farmers to bring their produce to viable markets, and the amount of market revenue they retain.

MESSAGE 2: MANAGEMENT PRACTICES THAT INCREASE AGRICULTURAL YIELDS ALSO IMPROVE WATER PRODUCTIVITY

Successful efforts to increase crop yields will increase water productivity, given that water productivity drops sharply at the low end of the yield curve (Fig 6b). In some cases, higher water productivity can be achieved, even if water use increases, provided that the proportional increase in yield is greater than the proportional increase in water use. Hence it makes sense to examine opportunities for improving crop yields in general, even though our primary concern involves water, given its limited availability and increasing scarcity.

There is substantial variation in crop yields and the corresponding water productivity values obtained for different crops and also for the same crop grown in different locations. This variation is due mainly to differences in soil and water management practices, thus implying that there is scope for improvement. Anything that improves the general vigor of a crop can generally also increase water productivity. Helpful measures involve the judicious, timely, more complete and more effective use of the water supply: capturing more water for transpiration and leaving less for unproductive evaporation (Figure 6a), more effectively exchanging water for CO_2 to produce biomass, and optimizing the development of the crop to ensure a large harvest index (ratio of yield over total biomass). The potential for significant gains in crop yield and water productivity occurs, when yields are low. Increasing yields from an already high level does not substantially raise water productivity (Figure 5).

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With a negative nutrient balance at 20 to 30 kg/ha of NPK (nitrogen, phosphorous and potassium) on a continental scale in sub-Sahara Africa, there is no alternative but to enhance soil fertility through innovative techniques of integrated nutrient management, including the use of chemical fertilizer along with biological nitrogen fixation, compost, manure and mulches. Resource-poor farmers in sub-Saharan Africa and South Asia, with perpetually low yields, are concerned with maximizing agronomic yields rather than optimizing returns. In other words, they wish to obtain an assured minimum yield in a bad year, rather than maximum yield in a good year, and providing food for the family in the immediate future rather than ensuring profitability over a longer time horizon. This risk-averse strategy is rational and understandable, but has contributed to the slow rate of adoption of improved agronomic practices particularly in sub-Saharan Africa.

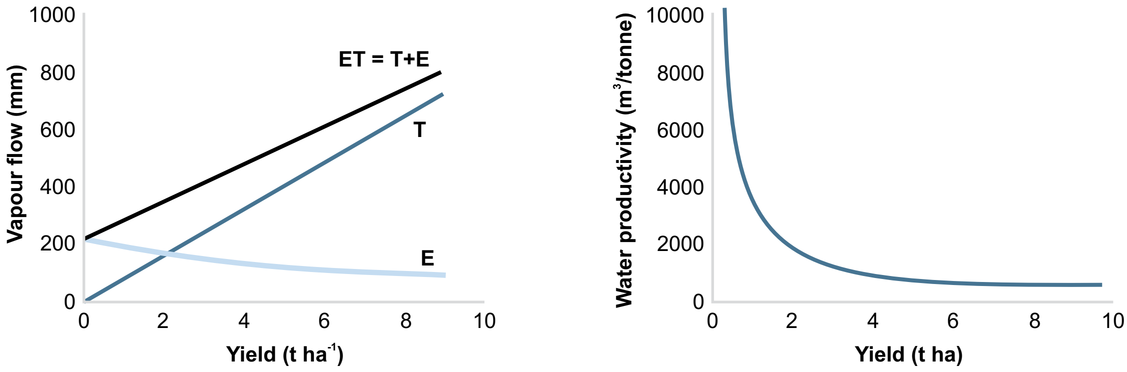

Figure 5: Water productivity and grain yield relation based on a synthesis of field measurements

(After Rockström, 2003; Rockström & Barron, 2007)

MESSAGE 3: THE GREATEST POTENTIAL TO INCREASE YIELDS AND WATER PRODUCTIVITY IS IN AREAS WHERE AGRICULTURAL PRODUCTIVITY IS CURRENTLY LOW

The difference in the yield of cereals between sub-Saharan Africa and other regions has widened considerably during the last 50 years. In 2004, for instance, the average cereal yield in East Asia and the Pacific region was about 4.5 t/ha while in sub-Saharan Africa (and parts of South Asia) it barely reached 2.5 t/ha. At the same time, the arable and permanent cropland per capita of the agricultural population is also shrinking in sub-Saharan Africa and South Asia (World Bank, 2007).

The remarkable gains in crop yields achieved in some portions of Asia and other regions in the 1960s and 1970s have not been achieved uniformly in all regions or on all farms. Millions of small-scale farmers, particularly in developing countries, and most notably in sub-Saharan Africa, obtain yields that are one-half, one-quarter, or even a smaller portion of the yields obtained on research stations (Figure 6).

Exploitable yield gaps, i.e. the difference between average national yields and the average yield in farm demonstrations, are high. Of the six sub-Saharan African countries reviewed in World Bank (2007, p. 67) the largest yield gap for maize production was observed in Malawi at 4.1 t/ha, and the lowest, 1.8 t/ha, was in Mali. The average for the six countries was about 2.7 t/ha. Depending on the actual yield level, this implies that for each ton of grain produced, there may potentially be a water productivity gain of 500-1000 m^3 per ton produced, moving from yield levels of 1 t ha^{-1} to 2-3 t ha^{-1} (cf. Figure 7).


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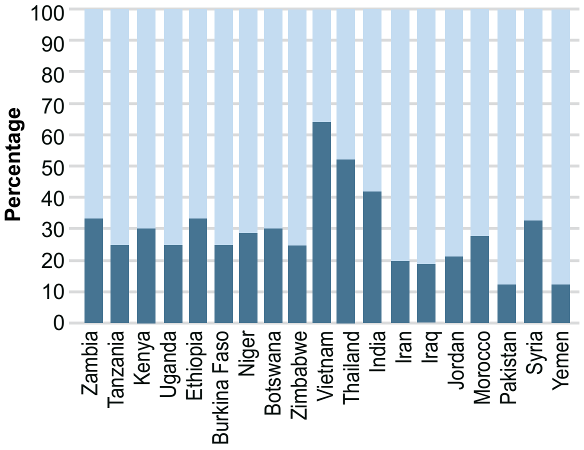
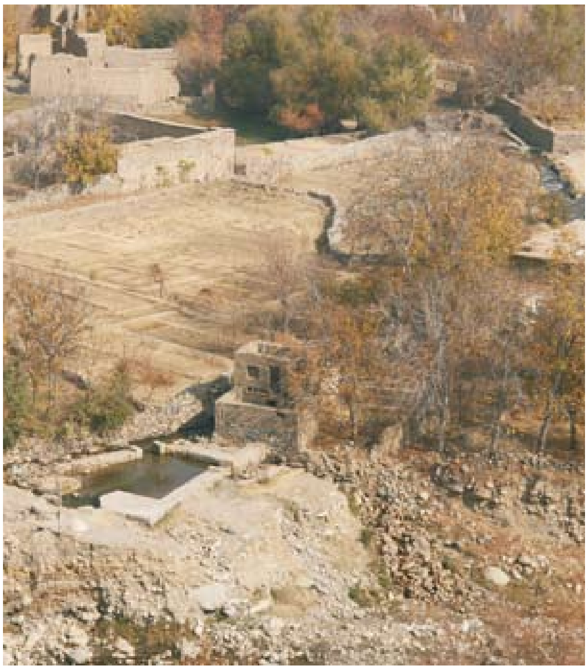


Figure 6: Examples of observed yield gap (for major grains) between farmers' yields and achievable yields (100 per cent denotes achievable yield level, and columns actual observed yield levels). (After Rockström *et al*., 2007)

The Comprehensive Assessment of water management in agriculture indicated that vast untapped potential of rainfed agriculture could be unlocked through knowledge–based management of land and water resources, bridging the yield gaps (a factor of two to four) between the current farmers' yield and the researcher managed or commercial plot yields (Wani *et al*., 2009; Rockström *et al*, 2007). A long-term experiment at the International Crops Research Institute for the Semi Arid Tropics, Patancheru, India since 1976, has shown a virtuous cycle of persistent yield increases through improved land, water, crop, and nutrient management in rainfed agriculture. An improved intercrop system of sorghum pigeon pea produced higher mean grain yields (5.1 t ha^{-1}) compared with 1.1 t ha^{-1}, the average yield of sorghum in the traditional (farmers') post-rainy system where crops are grown on stored soil moisture



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(Figure 5). The large yield gap between the attainable yield and the farmers' practice as well as between the attainable yield of 5.1 t ha^{-1} and potential yield of 7 t ha^{-1} shows that the large potential of rainfed agriculture remains to be tapped. This yield gap can be interpreted as an inefficient water use, i.e. sorghum crop produced at yield levels of 4 t ha^{-1} corresponds to an average water productivity of 1,400 m^3 t^{-1} grain, whereas 7 t ha^{-1} corresponds to circa 1,000 m^3 t $^{-1}$. In rainfed crop system, this suggests not that additional water may be available, but that yields were significantly increased with the same water availability.

The Comprehensive Assessment also revealed large yield gaps (Figure 6) for major rainfed crops in Asia and Africa and rainfed wheat in WANA with farmers' yields being a factor of two to four lower than achievable yields (Rockström *et al*., 2007). The vast potential of rainfed agriculture needs to be unlocked through knowledge-based management of natural resources for increasing productivity and income to achieve food security in the developing world.

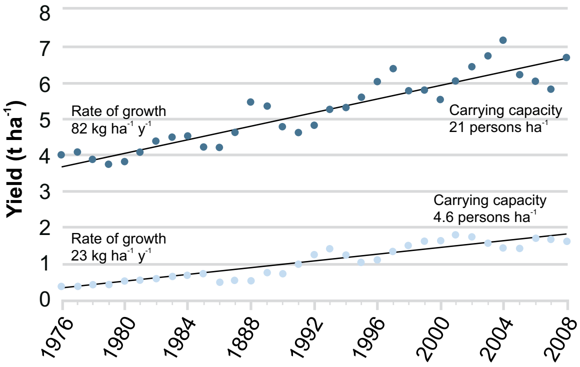

Figure 7: Three-year moving average of sorghum and pigeonpea grain yield under improved and traditional management in a deep Vertisol catchment at Patancheru, India.

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MESSAGE 4: MAJOR OPPORTUNITIES TO IMPROVE WATER PRODUCTIVITY ARE FOUND IN WATER MANAGEMENT PRACTICES ALONG THE CONTINUUM FROM RAINFED TO PARTIALLY AND FULLY IRRIGATED FARMING SYSTEMS

RAINFED AREAS

Key opportunities for improving water productivity in rainfed agriculture involve largely non-structural measures targeted at improving land husbandry and crop agronomy, such as in-situ water conservation, zero and minimum tillage, and mulch farming, and structural measures such as investments in capital works. Food and Agriculture Organization of United Nations (FAO) AO maintains there is ample opportunity[1] for developing new areas for rainfed crop production, particularly in sub-Saharan Africa and South and Central America (FAO, as quoted by Koohafkan and Stewart, 2008). According to FAO's land use models, nearly 700 million ha land in Africa are very or moderately suitable for rainfed cereal production. In 2000, only 340 million ha were under maize and wheat cultivation. Constraints on the production of rainfed cereal production in Africa arise from many factors including the poor institutional, infrastructural and financial capacities of African countries (Koohafkan en Stewart, 2008). However, for large parts of rainfed agriculture, variable rainfall and subsequent crop water availability is a major constraint causing low yields with poor water productivity. In the semiarid and dry sub humid zones, irregular crop water supply in rainfed agriculture can limit the adoption of new technologies including crop varieties, soil management, fertilizer and other promising management interventions. At present rainfed agriculture takes place on about 95per cent of the cropland in sub-Saharan Africa.

At field scale, interventions should aim to increase water productivity by reducing non-productive evaporation and/or increasing productive transpiration (see Figure 6). This can be achieved through agronomic improvements through investment in knowledge transfer. There is abundant evidence that mulching and appropriate soil management techniques are effective. Conservation agriculture (Gowing and Palmer, 2008; Rockström *et al*, 2009) has been shown to be effective in some circumstances, but its effectiveness in low rainfall environments requires further investigation.

IRRIGATED AREAS

Key opportunities in irrigated agriculture include the non-structural measures mentioned above, and also structural measures such as improving irrigation efficiency using micro-irrigation systems. In addition, it is essential to prevent seepage losses in the conveyance system and reduce evaporation during conveyance in areas where water is scarce. Actual losses depend on the state of the delivery network, and its engineering and management practices. After water arrives at the farm, it is sometimes temporarily stored, for example in night reservoirs, but more often it is directly distributed to the fields for irrigation. Losses at this stage are also due to leakage and evaporation. Losses in the application of water to famers' fields depend on the type of irrigation system, e.g. furrow, sprinkler or drip irrigation. Good water management requires that irrigation application do not exceed the amount of water that can be stored in the rootzone. In irrigated crop production, farmers can reuse drainage water and (treated) wastewater, while minimizing pre-planting irrigation, and managing the amount of water that infiltrates the soil and is stored in the rootzone.

Another approach to improving irrigated agriculture is to support high input irrigated production using high yielding varieties, fertilizers, pesticides and other inputs. This is increasingly difficult to achieve, as irrigation development in sub-Saharan Africa is expensive (see Message 10). Irrigated systems have been widely criticized for low efficiency in their use of water and the corollary is therefore that opportunities exist to increase water productivity. However, it is important to avoid

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[1] Much of the land classified as potential rainfed, is currently used for provision of other ecosystems services, including grazing land, forests and for example important habitats for wildlife. In reality even in sub-Sahara Africa, there is marginal opportunity for great agricultural expansion without compromising current landuse in these areas.

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problem shifting and recognize that apparent water losses may appear downstream as return flows. Where there are real water losses to non-productive uses, then farm-level adoption of water-saving irrigation technologies can increase water productivity. However, farmer adoption has been slow.

The World Bank (2006: page 165) notes there is a case for working with the private sector to achieve outreach and citing the case of drip irrigation in the Jordan Valley as a success story. Improvements can also be achieved with existing on-farm technologies through improving performance of the water delivery system. The World Bank (2006: page 157) advocates 'integrated modernization of existing large-scale irrigation systems' and cites the Office du Niger as a success story. This approach involves both hardware and software investments to bring about physical improvements to the water delivery systems together with improved agronomic practices and institutional change. Where the irrigated system exists within a closed or closing basin, opportunities to increase water productivity may best be found through multiple-use management of water. In particular, opportunities exist for investment in systems to promote re-use of treated municipal wastewater and/or agricultural drainage water.

DEFICIT AND SUPPLEMENTAL IRRIGATION

When water supply is insufficient to meet full crop water demand (or too expensive), alternative strategies of irrigation can be used, so called supplemental or deficit irrigation. Supplemental irrigation aims to add a limited amount during critical and water stress sensitive crop development stages, such as flowering and initial grain setting, or early establishment. Although this strategy has shown large potential to improve water productivity especially in semiarid and dry sub-humid cropping systems with high rainfall variability and high intra seasonal dry spell occurrence,(e.g., Barron, 2004; Pandey *et al*, 2001; Pandey *et al*, 2000) this is not a common practice to supplement rainfed agriculture in sub-Saharan Africa. Deficit irrigation is the deliberate management of crop water applications to create a prescribed water deficit that results in a small yield reduction, which is less than the concomitant reduction in evapotranspiration. The potential benefits of deficit irrigation arise from enhanced water productivity and lower production costs if one or more irrigation application can be eliminated. Irrigation systems in the Indian sub-continent had deficit irrigation built into the design when the systems were planned for low cropping intensities and water applications that fell short of the potential evapotranspiration. For deficit irrigation to be successful, farmers need to know the deficit that can be allowed at each of the growing stages and the level of water stress that already exists in the root zone. Most importantly farmers must have control over the timing and amount of irrigations. When water supplies are uncertain, as is the case with rainfall and unreliable irrigation supplies, deficit irrigation carries considerable risk for the farmers.

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MICRO-IRRIGATION METHODS

It is well known that the perceived or real wasteful use of water in irrigation can be reduced by the introduction of micro-irrigation, such as drip irrigation, as the applied irrigation is directly targeted to the root zone rather than being lost as soil evaporation and/or deep drainage. Investing in micro-irrigation and repairing the worst leaks in water distribution systems can indeed bring large savings. But usually farmers in poor countries can afford drip irrigation or other piped water distribution systems only if they are growing cash crops. Even a small rainwater tank is often lacking. Ethiopia, for example, has only 38 m^3 of water storage per inhabitant, compared to almost 5000 m^3 in Australia. Yet modest water storage can help to raise yields significantly in rainfed agriculture whether as supplemental–deficit irrigation over larger areas, or concentrated over smaller areas. Also, pumping water into natural aquifers for seasonal storage tends to be much cheaper than building a big dam[2], and prevents the large losses of water through evaporation from the water surface of large reservoirs, especially in arid and semi-arid (sub-) tropical countries. As mentioned, the efficient use of water is only one step toward achieving better agricultural yields. Farmers also need improved seeds and fertilizer. In Africa in particular, the absence of accessible and affordable improved seeds and agrochemical inputs such as fertilizer, coupled with inadequate pest and disease control often constitutes an equally large constraint on yields as the storage of water.

Drip (or trickle) irrigation has considerable advantages over furrow or even sprinkler irrigation in terms of water application efficiency. Nevertheless, this type of irrigation is no panacea. Competent operators can achieve high efficiency, but incompetent ones can be just as wasteful as with conventional irrigation systems (Hillel, 2008). The narrow orifices of drip emitters are prone to clogging by sand particles, chemicals or algae carried in the water. In drip irrigation only a fraction, often as little

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[2] The 5th World Water Forum, recently held in Istanbul, stressed the need for the construction of additional large storage dams in order to cope with increasing water scarcity (Economist.com 21 March 2009).

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as half, of the soil volume is wetted. Many crops can thrive under those conditions, but any disruption in the water supply, for example as a result of a power outage, can be detrimental and cause crop failure. Ready-made commercial technology often fails when introduced into developing countries without proper instruction and sources of support and maintenance. According to Hillel (2008), the highly complex assemblages developed to serve drip irrigation systems in western countries obscure the concept's essential simplicity. Capital- and energy-intensive complicated systems are only justified when it is necessary to reduce labor costs, which is usually not the case in developing countries. Hence, for developing countries, simplified systems may be preferable for facilitating installation and maintenance, while retaining the basic principles of efficient water use. (See Box.)

WATER HARVESTING

For smallholder rainfed systems, dry spell occurrences during seasons and in between seasons has severely undermined food security and general livelihoods, particularly in sub-Saharan Africa. In order to augment their scarce supplies farmers often turn to pumping groundwater and the collection of surface water through the development of water harvesting structures. Productivity of rain in semi-arid environments is often low. Water harvesting is the collective name for a range of technologies that aim to concentrate water flows and storage, either as in-situ technologies (in principal using the soil as storage of infiltrated rainfall), or in natural or manmade storage structures such as dams, ponds and tanks. With successful water harvesting techniques, over 50 per cent of lost water can be recovered at relatively little cost, as shown in studies in the dry rainfed regions of the Middle East and North Africa (Oweis and Hachum, 2006). However, socio-economic and environmental benefits of this practice can be more important than increasing crop water productivity if better water management is combined with improved farm management practices, including better crop selection and appropriate cultural practices (e.g., UNEP-SEI, 2009).

The development of water harvesting structures upstream of a water storage reservoir can have the unintended consequence of drastically reducing the

Micro-irrigation technologies

Governments and NGO's have promoted the introduction of micro-irrigation technologies because they allow better control over water delivery and hence may lead to higher water productivities. They have also provided institutional support. In spite of this support, the current micro-irrigation area in India remains a small proportion of its potential. A study by Namara et al. (2007), showed that micro-irrigation technologies in India resulted in significant productivity improvement and financial benefits compared with the traditional method of surface irrigation. The authors also studied those who adopted the technology and why. Access to groundwater, the prevailing cropping pattern (adopters were farmers growing more high value crops), level of education, availability of cash, and the wealth or poverty status of the farmer all affected the adoption process. Most of the current adopters of low-cost micro-irrigation systems belong to the richer section of the farming population.

Thus, reducing the cost of micro-irrigation technology alone is unlikely to improve poverty outreach of these technologies. In view of the limited groundwater supply in the study areas, the long-term sustainability of micro-irrigation systems appears to depend on how much productivity improved after shifting from surface irrigation to micro-irrigation, and whether more farmers decided to shift from the production of staple crops to high value crops with higher water demands.

Source: Namara et al., 2007

inflow into a downstream reservoir (tank). This is illustrated by the results from a study in Andra Pradesh and Karnataka in India (Johnson, 2007), where a large increase in the number of water harvesting structures decreased the average retained tank inflow by 64 per cent and the average annual duration the tank was filled to more than one-tenth of its capacity by 69 per cent. This resulted in a less reliable source of domestic water supply for the villagers who obtained their drinking water from the tank. This obviously calls for better integrated planning process of water harvesting structures involving all potential stakeholders (see Message 6 and 7).

The link between rainwater management and climate change has been studied in semi arid areas of southern Africa. Tsubo and Walker (2007) found that the risk of low yields resulting from variable rainfall due to the El Niño-Southern Oscillation (ENSO) phenomenon can be reduced if rainwater is collected in micro catchments in a semi-arid region (Bloemfontein, South Africa). A weather-crop growth model was used to estimate maize yield in the water harvesting production system. Depending on seasonal characteristics, yields were improved with micro catchments (in-situ rain water harvesting) and supplemental irrigation. In addition, different management strategies were important to maximize yields, including varied plant density and optimum yield varied with planting density as well as planting date and different cultivars. Reliable seasonal rainfall forecasting would enable farmers to decide whether

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they should attempt water harvesting in the growing season and which plant density to apply. It is only in El Niño years these efforts would pay off in higher yields (Tsubo and Walker, 2007).

A study in Tanzania by Makurira *et al*. (2007) showed that rainwater alone is not sufficient to obtain good yields of maize, the preferred staple food crop. It is necessary to employ a combination of improved tillage and rainwater harvesting techniques to help boost crop yields. The study showed that with rainfall in the range of 186 to 403 mm/season yields as high as 4.8 t $ha-1$ can be achieved with better soil management and more efficient soil moisture retention techniques. This yield compares to yields of less than 1 t $ha-1$ that are achieved without these techniques. Water is limiting productivity but a combination of rainwater harvesting for supplemental irrigation and conservation agriculture can improve grain yields by as much as 80 per cent. In this instance, using manure or cover crops did not significantly improve yields.

Elsewhere, the use of water harvesting for supplemental irrigation combined with fertilizers has shown the highest yields in field trials in semi arid Kenya (Barron and Okwach, 2005) and Burkina Faso (Fox and Rockström, 2004), with correspondingly large gains in water productivity. The main conclusion is that securing crop water availability is the first step, but no major yield gain will be obtained without also addressing nutrient status and other management issues. Consequently, water productivity will not necessarily improve with better water availability alone as yield gains are marginal. Water productivity will only improve when yields increase due to multiple improved cropping conditions, where water management is a starting point for further improvements in fertilizer, weed and pest management and timely interventions, i.e., closing the yield gap (see Message 3).

Small-scale farmers in Zimbabwe face similar problems to the farmers in Tanzania. Zimbabwe's poor are also predominantly located in the semi-arid regions and rely on rainfed agriculture for their subsistence. A recent study (Mwenge Kahinda *et al*., 2007) in six semi-arid districts of Zimbabwe suggests that water productivity improved with a combination of supplemental irrigation and fertilizers. The Agricultural Production Simulator Model (APSIM) was used to simulate seven different treatments (various combinations of rainwater harvesting and fertilizer applications) for a 30-year period on a sandy soil. The combined use of inorganic fertilizer and water harvesting for supplemental irrigation was found to be the only treatment that brought yields up to their potential level. Supplemental irrigation alone not only reduces the risks of complete crop failure for all the treatments but also enhances the water productivity from 1.75 kg $mT-3$ (transpired water) up to an average of 2.3 kg $mT-3$ thus mitigating the effect of short-duration drought periods.

MESSAGE 5: WATER PRODUCTIVITY GAINS ARE REALIZED ALSO BY NON-WATER MANAGEMENT INTERVENTIONS

About 90 per cent of the world's food supply is provided by no more than 17 plant species and these crops occupy about 75 per cent of the total cultivated land on earth. Eight cereal grains – wheat, barley, oats, rye, rice, maize, sorghum and millet – provide 56 per cent of the food energy and 50 per cent of human protein consumption. Cereals are the most important source of total consumption in the developing world, providing about two-thirds of total calories. Wheat and rice are by far the most widely consumed cereals in the world. Wheat, rice and maize make up about 85 per cent of the world's production of cereals (Koohafkan and Stewart, 2008). Clearly, continued allocation of water for the production of cereals is a high priority for food security and poverty reduction. So too, is continued research and development of genetic enhancements and production activities that will increase crop yields, whilst improving efficient use of water, nutrients and land use.

Several plant characteristics have been improved, which has improved water use during growth and thus, water productivity. In both rainfed and irrigated crop production, crops take up only some part of the water applied to the field. Water that evaporates from wet soil surfaces and water left in the soil at harvest time are losses, although the stored water may benefit a subsequent crop.

The partitioning between transpiration and soil evaporation differs between crops and varieties. For some crops, plant breeding has been successful in shortening the time until complete soil cover is achieved, and consequently soil evaporation is reduced. Crops also differ in their ability to assimilate CO_2 by photosynthesis, relative to the volume of water transpired, as well as in actual biomass conversion, the amount of biomass produced relative to the mass of carbon dioxide assimilated. The chemical composition of the crop governs biomass conversion, which, according to Hsiao and co-workers (2007), is not easily changed, except for possible temperature-induced changes in respiration rate.

The harvest index, which describes the portion of plant biomass that becomes harvested yield; is also an important characteristic. Some plant physiologists believe that the harvest index of most staple grains has already been increased as much as possible during the Green Revolution with the introduction of high-yielding varieties and improved agronomic practices (Richards, 2006). Others are optimistic about possible further increases in harvest index, especially for crops that were not part of the Green Revolution (Bennett, 2003).

Plant breeding continues also for the well-known cereal crops as is demonstrated by a recent study (Gutiérrez *et al*., 2009) that discusses germplasm exchange for genetic gain in an international breeding program of barley. Considerable genetic diversity was found and the study identified breeding programs with similar objectives and environments of selection (so-called mega-targets of selection). The identification of compatible programs for germplasm exchange is likely to be relevant for improving genetic gains in breeding programs, and this study could serve as a model for other international germplasm exchange programs. See also the recent special issue on abiotic stress, published by Molecular Plant (Bressan *et al*., 2009).

Morison *et al*., (2008) found that in water-scarce environments about half of yield improvements are due to improvements in the crop, and half due to improved agronomy and management practices. These two efforts have complemented each other. Although it is generally well understood why yields are limited under drought there has been only limited progress in improving yields through selecting physiological traits. This is due in large part to the unpredictability of drought periods and their intensity. According to Morison *et al*., (ibid.) "*In some areas, yield depends entirely on water stored in the soil profile, in others on current rainfall only, while for many areas plant yield is a result of water available from soil stores, rainfall and irrigation. These variations mean that there are many and varied targets for plant improvement under drought*".

Progress in increasing crop yields in drought-prone areas has been made by selecting plants for a variety of characteristics all of which aim to increase the harvest index, mainly by making relatively more water available for transpiration, or by manipulating development stages such that the chance of severe drought stress during vital phases of reproductive development of the crop is reduced. Among others, Bennett (2003) concluded that there was only low probability of achieving more photosynthesis per unit of water transpired (i.e., transpiration efficiency) but medium to high probability of achieving other improvements including higher harvest index. There is scope for decentralized breeding combined with farmer participatory methods to develop better crop varieties. As noted in the report, combining better varieties with better management will result in higher yield and increased water productivity. Interventions aimed at closing the yield gap by overcoming input supply constraints will contribute to this improvement.

Passioura (2006) mentions that modifying these traits is not a short-term stress-tolerance response; the changes operate over the life of the crop, or at least during key developmental periods. Morison *et al*., (2008) demonstrate that meeting the basic requirement for water in crop production involves many interlinked processes and is in fact quite complicated. Progress requires understanding in all disciplines of relevance to crop production. The authors are of the opinion that the development and release of new varieties or ones with different characteristics will improve water productivity through combined physiological, biotechnological and agronomic research. Unfortunately, however, many of the more technologically demanding approaches are unlikely to be appropriate or available to small farmers.

The potential in sub-Saharan Africa to benefit from technological advances from outside the region is smaller than elsewhere. In part this results from the crops grown there, which are more diverse than elsewhere and include a number of so-called orphan crops (e.g., cassava, yams, millet, plantain and teff). In recent years several of the CGIAR institutes have included one of more of these crops among their mandated crops, and this collective research endeavor should lead to productivity gains. There are many projects for the development of heat-

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Water productivity and abiotic stresses on crops: ozone impacts on yield in South Asia

Where water productivity (WP) increases with yield increases, the opposite is true for increases in certain abiotic stresses. Crop production systems subject to such stresses will decrease yields without equal decreases in water use. An example of this are the impacts on yield resulting from ground level ozone in South Asia (Emberson et al., 2009) with evidence suggesting that high ozone concentrations are causing substantial yield losses, commonly reaching 30 per cent in regions across South Asia, also in the 'bread basket' of the Indo-Gagnetic plains.

Current average cereal yield in the Indo-Gagnetic plain is 2.5 t ha^{-1}, i.e. a WP =1,500 m^3 t^{-1}. If this yield level represent a 30 per cent suppressed level due to existing ozone impacts, the potential obtainable yields could be in the region of 3.25 t ha^{-1}, with a corresponding WP of 1,300 m^3 t^{-1}. Assuming cereal production takes place on 70 per cent of the 114 million ha of net crop area in the Indo-Gagnetic basin, this water productivity gain potentially corresponds to a reduced area of crops of 30 per cent. Alternatively, the water productivity gain could translate to reduced need of water in the order of 40 km^3 per year for producing the same total yield of 200 million tons of grain.

Future estimates of climate change, including temperature increases and unreliable rainfall patterns for the region, may add stress to crop production. In addition current development trajectories, will further add to current high atmospheric ozone levels and potential crop damages. Thus, addressing opportunities for water productivity gains may sometimes lie far beyond the conventional water management arena.

and drought-resistant varieties of staple crops under way. A project in southern Africa, for example, involving the International Maize and Wheat Improvement Center (CIMMYT) and partners has released drought-tolerant maize varieties that yield about one-third more than farmers' existing varieties in Malawi, South Africa, Tanzania and Zimbabwe. CIMMYT scientists are also working on developing wheat varieties that are well suited to zero-tillage farming, as well as heat-tolerant, for farmers in the Indo-Gangetic Plain of India (IFPRI, 2006).

Gowda *et al*. (2009) review genetic enhancement of dryland crops with a view to improving crop water productivity. The review focuses on pearl millet, sorghum, groundnut, chickpea and pigeon pea, all mandated crops of the International Crops Research Institute for Semi-Arid Tropics (ICRISAT), and rainfed maize. Recent research has succeeded in identifying simple and effective traits associated with drought tolerance. As a result of these approaches, several genetically enhanced products have been developed, some of which have reached the farmers' fields. Products of marker-assisted selection in pearl millet and maize have shown superior performance under severe drought-stress conditions, but no advantage yet under mild or no stress conditions. Clearly, further research on these crops will bring additional improvements. Other successful plant breeding studies are reported among others by Richards (2006) and Dingkuhn *et al*.(2006).

Good nutrient management in addition to securing adequate crop water supply is imperative to improve water productivity. In a synthesis of field trials with different nitrogen levels and deficit irrigation strategies, carried out in arid to semi arid locations, Zwart and Bastiaanssen (2004) showed that often water productivity reached an optimum level depending on the amount of nitrogen application. When this optimum N application was exceeded, no further gains in water productivity were obtained.

Passioura (2006) discusses yield data available from studies of winter wheat in relation to rainfed water supply in southern Australia, a climatically Mediterranean environment. He compared simulated yields of well-managed rain-fed wheat and mean annual reported yields (kg/ha) in southern Australia against growing-season rainfall (mm). Passioura (ibid.) identified an upper limit of the transpiration efficiency (i.e., the net exchange by leaves between water and CO_2 leading to the production of biomass[3]) of 20 kg ha^{-1} mm^{-1}, which is rarely exceeded

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[3] Transpiration efficiency depends on photosynthetic type (C3, C4, CAM) and on the evaporative demand of the environment. It is well-known that transpiration efficiencies of C4 plants are larger than those of C3 plants at the level of gas exchange of leaves. However, the difference between the two in water productivity is probably smaller in the field (Passioura, 2006)

in farmers' fields. The simulated yield data assumed that the crops are well managed and disease-free. Except in the driest years, actual yields were often much below the simulated yields due to the variable intra-season rainfall distribution in the growing season. Water deficits at a critical period, such as flowering, can lead to low yields even though the seasonal rainfall may have been adequate. Although weeds, disease, poor nutrition, frost, heat, and even waterlogging in the wetter years may have caused these low yields, the distribution of the data points also suggests that other factors than water were limiting yields in most years, something also observed in several studies from sub-Saharan Africa. Discrepancies between actual and expected water-limited yields can reveal other plant- or soil-related limitations such as inadequate nutrition, hitherto unrecognized root diseases, inadequate rooting depth (due to compaction, rocky or saline subsoil), inappropriate choice of cultivar, poor establishment, or inadequate infiltration. As Passioura (ibid.) says "*If such limitations do become evident, then dealing with them where possible is likely to bring the largest and fastest rewards.*"

At field level, the need to manage soil and water together translates into a well-defined set of good agronomic practices. These practices include the timeliness of farmers' operation - seeding, planting, weeding and harvesting - in addition to the practice aiming to secure rainfall infiltration and application of additional water as irrigation. These good practices and others have been described extensively in the literature together with the constraints that keep farmers from adopting them (see, for instance, Kijne, 2003, Hsiao *et al*., 2007, Bossio *et al*., 2008, and Molden *et al*., 2009). As mentioned, variability in farmers' yield and the water productivity they achieve in their fields is high and generally ascribed to differences in the natural conditions of their fields and farmers' management practices. We often think in terms of average values and tend to forget that many farmers achieve higher yields or higher productivity depicted in the average values. As in all other professions, some farmers are better at their task than others.

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MESSAGE 6: IMPROVING LIVESTOCK WATER PRODUCTIVITY SHOULD BE AN INTEGRAL PART OF WATER RESOURCE MANAGEMENT

Worldwide, livestock production takes place on more land area than crop production and makes a major contribution to agricultural GDP (Peden *et al*. 2007), livelihoods and in particular smallholder farming systems incomes. In recent years, global consumption of meat and milk have been growing at 2.1 per cent and 1.7 per cent respectively, higher than the rates of increase in production. Much of this increase in consumption and production takes place in developing countries, where many people derive their livelihood from keeping domestic animals. The intensification of livestock production, and inappropriate management practices have contributed to land and water degradation. In Asia, crop-livestock mixed systems already predominate, but also in West Africa a transition is taking place from pastoralism and shifting cultivation to mixed farming systems that are associated with a relative low level of farming system intensification (Steinfeld *et al*., 2006).

The challenge for livestock production is epitomized in the expected doubling of meat consumption in East Asia between now and 2050, due to economic growth in this region. A global increase in consumption of livestock products must lead to higher feed grain demands. Livestock are fed by grass, crop residues and feedstuffs (mainly barley, maize, wheat and soya) in different combinations. The experts are not in agreement on how livestock will be fed in the future. Will cattle on a global scale continue to be raised largely on grass and crop residues or will grain feeding become more important when the opportunities to expand grazing land decline? If it is the latter, feed demand will drive future demand for grains and farm managers will be pressed to increase water productivity in feedstuff production (Steinfeld *et al*., 2006).

The productivity of water in livestock production is defined as the ratio of net beneficial outputs from livestock production to the amount of water depleted (in evapotranspiration and pollution). The numerator of the productivity term includes products such as milk, meat and eggs, but also manure as fuel and for use as fertilizer, services such as draught power, and social benefits of livestock, including status symbols, savings and wedding presents. Clearly, the water productivity concept is more complicated in livestock production systems than in crop production, since assessing the social benefits of livestock production in monetary terms is subjective and difficult. If animals graze on the stubble of cereal crops, the water used to grow the crop is counted in crop water productivity and the opportunity cost of the stubble is often negligible. Likewise, feeding animals other crop residues, such as cotton cakes, increases the water productivity of crop production. In those cases the concept of livestock water productivity becomes rather meaningless. However, when crops are grown explicitly for cattle feed, e.g. alfalfa for pellets to be fed to cattle, the (irrigation) water depleted in the production of the alfalfa has

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Water use in livestock production

How much water is already being used in the production of feed stuffs for livestock is not clear. Recent reports give two different approaches to calculate the amount of water consumed in livestock keeping. One, a spatially detailed water balance calculation, indicates that about 10 per cent of the global water used ("evapotranspired") in irrigated crop production is used in growing barley, maize, wheat and soybean for feed (Steinfeld *et al*., 2006). If these four crops constitute about 75 per cent of the total feed requirement, the total share of water evapotranspired for irrigated feed production is about 15 per cent of the global amount of water used in producing irrigated crops. Similarly, also about 10 to 11 percent of the global amount of water evapotranspired in rainfed cropland was found to be involved in the production of the four crops, barley, maize, wheat and soybean grown for feed. According to this analysis, globally 15 per cent of the water evapotranspired in agriculture is consumed by feed crops, including grassland and forage.

Peden *et al*. (2007) use a different set of assumptions and estimated values to calculate the amount of water used in the production of feed crops. This calculation involves the feed energy supplied per kg of grass or feed crops, the average feed energy requirements per animal, the mix of feeds for different kinds of livestock, and the water productivity of feed crop and grass production. For all developing countries taken together this approach leads to an estimated water need of 536 km^3 for maintenance of livestock (including only cattle, sheep and goats). Maintenance refers to the minimum amount of water needed to keep animals alive without weight loss but excludes extra feed needed for growth, lactation, and work. The approach estimates the global water used to produce feed at 1300 km^3, which includes the demand for all other livestock species and takes into account requirements beyond the basic maintenance needs. This estimate corresponds to 18 per cent of the global evapotranspiration in agriculture (7130 km^3). Considering the many assumptions made in both sets of calculations, the best estimate that can now be made is that between 15 and 20 percent of the global water use in agriculture is associated with the production of livestock products.
(Source: Kijne, 2008)

an opportunity cost. In those cases, livestock water productivity is an important parameter in deciding how to allocate a scarce water resource. A case in point is the use of scarce groundwater from the Ogallala aquifer in the western USA for the production of alfalfa for livestock production. The global amount of water used in livestock production is only known approximately (see Box.)

The opportunity cost of rainwater falling on grazing land is usually low. Calculating a water productivity value for livestock keeping on grazing land is meaningful if there is a significant opportunity cost of the water. For instance, such a value would be useful if the rainwater could be applied domestically or for food production making use of water harvesting techniques, but also when the water serves an ecological need such as maintaining a wetland (Peden *et al*., 2007).

Water productivity of animal products is often said to be far lower than that of crops. However, when water productivities are expressed as dry weight per cubic meter the difference is less. For example, a typical value of water productivity of maize (kg dry weight/m^3) is 1.4 versus milk of 1.3 and poultry meat 0.24. Likewise water productivity expressed as gram protein per cubic meter is 77 for maize, 40 for milk and 33 for poultry meat (Renault and Wallender, 2000).

Studies conducted by the International Livestock Research Institute in the Nile valley indicate that the productivity of water used in livestock farming, counting the multiple uses of livestock, compares favorably with the productivity of water depleted in the production of horticultural crops (Peden *et al*., 2008). Based on these studies, researchers have formulated four major strategies for increasing livestock water productivity: (1) providing feeds composed of crops that can be produced with high crop water productivities (apart from plant residues and byproducts, further studies are needed to identify these high water productivity feeds) ; (2) using marketing, improved veterinary health services, and nutrition to maximize potential benefits from animal products and services; (3) adopting animal management practices that prevent soil compaction and therefore reduce erosion, runoff and water pollution, and promote grass growth, and (4) spatially allocating watering sites to balance supply and demand for animal feed and drinking water (Peden *et al*., 2008).

MESSAGE 7: WATER PRODUCTIVITY GAINS IN AGRICULTURE CAN SECURE WATER RESOURCES FOR OTHER LANDSCAPE USES AND ECOSYSTEM SERVICES

Most of the increases in food production achieved in recent decades have been achieved by expanding the area used to grow crops and raise livestock. Intensification of agriculture has also played a notable role in increasing the yields of crop and livestock products, particularly in irrigated areas. Some of the expansion and intensification of agriculture has degraded natural ecosystems. In some areas, the degradation has harmed native plants and animals, reduced stream flows, and diminished the quality of wildlife habitat. In other areas, inappropriate land and water management have impaired agricultural sustainability. Notable examples include areas where groundwater overdraft has caused falling groundwater tables, and where inadequate water management has resulted in waterlogging and salinization that reduce crop yields and degrade the quality of land and water resources.

The largest area expansions during the second half of the previous century took place in sub-Saharan Africa (SSA) and the Middle East/North Africa (MENA), whereas in the other regions agricultural production increased mainly as a result of yield improvements (Figure 7). There is no reason to assume that future growth in production in sub-Saharan Africa, North Africa and the Middle East will continue to be driven relatively more by area growth than in the other regions, given increasing competition for land by urban expansion and for biofuel production. To the contrary, Runge *et al*. (2003) suggest that future growth in agricultural production should be the result of technological change that increases output and lowers production costs, investments that reduce transport costs and open markets, widespread participation in agricultural markets by small-holder and women farmers, and by significant reforms in natural resource management.

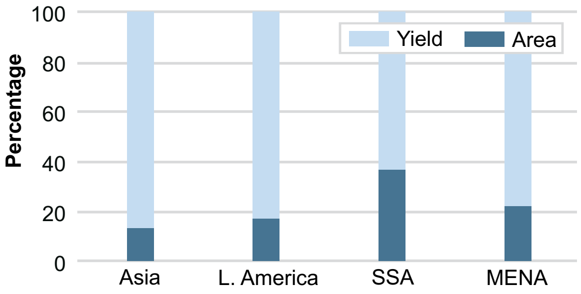

Figure 7: Sources of agricultural production growth, 1961-2000 (percent). SSA is Sub-SaharaAfrica, MENA is Middle East and North Africa. (After Runge *et al*., 2003)

Successful efforts to increase water productivity can reduce the need for blue water withdrawals, leaving more river runoff for aquatic ecosystems. Improvements in water productivity can also limit the need for further expansion of agriculture on to lands that might provide other desirable ecosystem services, such as wetlands, forests, and grasslands. Obtaining higher yields on existing lands will also reduce the areal extent of tillage, fertilizer application, pesticide use, and other agricultural activities that can degrade the quality of ecosystem services, if conducted with inadequate concern for the environment. To some extent, but not exclusively, successful efforts to increase water productivity will involve intensification of agricultural practices.

At scales larger than farm fields and irrigation systems more water users are in play and more interactions between stakeholders need to be considered. Water productivity issues become increasingly complex at watershed level. Good management of water at local level needs the support of a sound policy framework at regional and national level.

A major opportunity to improve water productivity at watershed, basin or national level lies in green water use, complementing the conventional ways of managing the blue water resources. Other ecosystem services besides food production (e.g. biofuels, carbon sequestration, biodiversity etc) depend almost exclusively on green water. Any improvement in

Water productivity, water footprints and virtual water

Water productivity, the amount of water appropriated to produce or consume a given goods or service, is increasingly being used in the context of water foot printing. It is being used a s a measure (similar to carbon footprinting) to assess and compare for example diets, consumption patterns and even production processes in terms of water appropriation. An example of easy to use calculators on water footprints is available at www.waterfootprint.org

Water productivity for goods and services are also used in the concept of virtual water, i.e., the estimate of water required to produce specific goods and services, which are traded. As water productivity for a given produce varies by production management, high/low intensity as well as climate, some argue that the virtual water trade will be increasingly important as nations or regions move towards water scarcity.

green or blue water productivity in agriculture can help to allocate more land and green water to these other ecosystem services

In large river basins, effective governance from local to basin levels is an even greater challenge than at watershed level. Competition for water, resource degradation, and issues of equity are most apparent in such large river basins, especially when it involves cross-boundary rivers. Changing water allocation at basin level involves significant trade-offs. A key requirement of any trade-off analysis is a thorough hydrological understanding of potential changes in quality, quantity, and timing of water for different uses. Assessing the impact of a change in water allocation involves the analysis of benefits and costs, and assessing which of the stakeholders will benefit and who will pay the cost. Most difficult to evaluate are those cases where better water management involves tradeoffs between different social objectives. Decisions made about the balance between livelihoods, energy production and environmental protection should reflect local priorities, which are inherently subjective (Lenton and Muller, 2009). There are many examples where engagement in better water management has improved the environment and also brought social and economic benefits. Often, as these authors mention, priorities for water management will change, reflecting the political priorities of the times.

INTEGRATED WATERSHED MANAGEMENT: AN EXAMPLE FROM INDIAN MICRO-WATERSHED MANAGEMENT

A holistic approach to water productivity improvements can be seen in the extensive integrated watershed management strategy for developing vast dryland areas adopted by the Government of India. By essentially

Table 2. Summary of benefits from the sample watersheds

	Particulars	Unit	No. of studies	Mean	Mode	Median	Minimum	Maximum	t-value
Efficiency	B:C ratio	Ratio	311	2.0	1.7	1.7	0.8	7.3	35.09
	IRR	Per cent	162	27.40	25.9	25.0	2.0	102.7	21.75
Equity	Employ-ment	Person days/ ha/ year	99	154.50	286.7	56.5	5.00	900.0	8.13
Sustaina-bility	Increase in irrigated area	Per cent	93	51.5	34.0	32.4	1.23	204	10.94
	Increase in Cropping intensity	Per cent	339	35.5	5.0	21.0	3.0	283.0	14.96
	Runoff reduced	Per cent	83	45.7	43.3	42.5	0.34	96.0	9.36
	Soil loss saved	Tons/ha / year	72	1.1	0.9	1.0	0.1	2.0	47.21

managing rainfall and inflows of water in a given watershed more efficiently and beneficially for local populations, a range of locally important natural and social features have improved (Wani *et al.* 2008). An ICRISAT-led consortium carried out a meta-analysis of 636 Indian micro-watersheds. The evidence clearly revealed that watershed programs are providing multiple benefits through the improved management of landscape water resources benefiting both livelihoods and the environment. It showed augmented rural incomes, generating rural employment (150 person days ha^{-1}), increased crop yields, increased cropping intensity (35.5 per cent), reduced runoff (45 per cent) and soil loss (1.1 t ha^{-1}), augmented groundwater, building social capital and reducing poverty. In terms of economic efficiency watersheds generated an average benefit cost ratio (BCR) of 2, and only 0.6 per cent of watersheds failed to give a return to the investment (benefit cost ratio less than one), as shown in Figure 8 (Joshi *et al*. 2008). The internal rate of return (IRR) from the watersheds investment was 27.4 per cent. Thirty two percent of watersheds showed a mean BCR of greater than two and 27 per cent of watersheds yielded an IRR of more than 30 per cent, which showed immense potential to upgrade watershed programs in the country (Table 2). Thus, water productivity gains, as in using water more efficiently can improve both human and environmental well-being, also in challenging poverty affected tropical drylands.

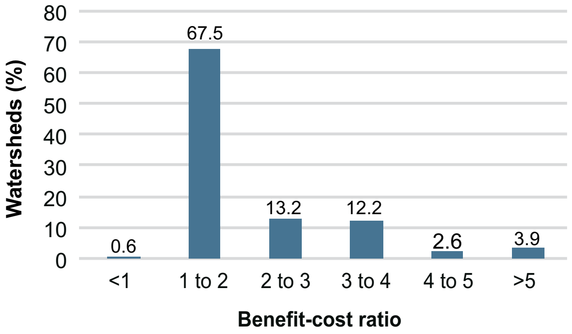

Figure 8: Distribution (%) of watersheds according to benefit-cost ratio (BCR).

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MESSAGE 8: INTEGRATED WATER AND LAND MANAGEMENT AT THE WATERSHED SCALE IS KEY TO IMPROVING WATER PRODUCTIVITY AND ENABLING SUSTAINABLE WATER RESOURCE MANAGEMENT

Of the 100,000 km^3 of water that falls on the land each year, an estimated 35 per cent results in blue water, i.e., rivers, lakes, reservoirs and aquifers, and 65 per cent becomes green water, i.e. water contained in the root zone of the soil. Effective integrated water resource management should include both green and blue resources to identify opportunities, constraints and potential trade-offs. Both green and blue water originate from rainfall within a catchment area. Rain that does not infiltrate the soil surface runs off into depressions, creeks and rivers and possibly from there into reservoirs. Some of the rainwater that infiltrates the soil cannot be retained within the soil profile because the soil's water holding capacity is limited. That excess water seeps down into an underlying aquifer, from where it could recharge shallow groundwater, or be pumped up in case of deeper recharge. Some of the water in rivers and reservoirs also seeps down to aquifers.

Obviously, the partitioning of rainfall into green and blue water is largely driven by land use, and green and blue water are intimately linked. Both types of water are under growing pressure from agricultural demands, reliant water supply for consumption and development, as well as environmental flow requirements in river, lakes and wetlands. Easy access to additional blue water is coming to an end in many regions of the world (Figure 1a). Several river basins are closed or approaching closure in that the available blue water resources are fully allocated. In closed basins, additional water commitments for domestic, industrial, agricultural or environmental uses can only be fulfilled by reducing some existing uses during all or part of the year. Already at least 1.4 billion people are estimated to live in such areas (Falkenmark and Molden, 2008). Moreover, expanding water pollution, salinization and overexploitation of groundwater, indicate that we have reached a limit of blue water use in many regions. Green water scarcity often results from soil and land degradation, the effect of overgrazing, erosion, and poor soil management, now exacerbated by population pressure and climate change. A new name for the present and looming threat of amplified water scarcity of blue and green water sources is 'peak water' (Falkenmark, 2008), implying that as future demand for water grows its availability in many places will diminish, which is shown in Figure 1b. As Falkenmark (2008) points out, the urgency of this situation has not yet been recognized widely.

According to Rockström *et al.* (2009) and others, green water (water contained in the soil after rainfall that is available for plant growth) dominates in food production. Global consumptive use of green water is four times that of blue water (fresh water in rivers, reservoirs and aquifers). Model studies indicate that many blue water-scarce countries could be self-sufficient in food production if their green water resource were managed better. Comparing accessibility of green and blue water for agricultural production is difficult. The authors mention the example of the Niger River, which passes through the southern tip of Niger, suggesting a high availability of blue water per capita in the country, though most of the population has no access to the river's water. Likewise disregarding spatial variation in rainfall distribution can give the wrong impression about local accessibility to water. Most sub-Saharan African countries are not water-scarce in theory, but in practice access to water is a huge problem for most of the people (e.g., Vorosmarty, 2005). Nevertheless, both green and blue water can be managed much better so that the total productivity of water resources is raised.

INTEGRATED WATER RESOURCE MANAGEMENT

Improving water productivity is part of sustainable water resources development and management.

In efforts to improve water and land resources, the concept of water productivity can assist negotiations and present new opportunities and degrees of freedom. Integrated water and land resource management should take into account long-term planning needs as well as short-term, immediate needs. It should incorporate environmental, economic and social considerations, and constitute an integral part of the socio-economic development planning process. It should also include the requirements of all water users and of those involved in the prevention and mitigation of water-related hazards (Lenton and Muller, 2009). These sentences paraphrase the definition of Integrated Water Resources Management as developed at the Earth Summit in Rio de Janeiro in 1992. Over the years, some considered IWRM as a blueprint package for all situations (e.g., Biswas, 2004). But as Lenton and Muller (ibid.) make clear, it is an approach rather than a method or a prescription. Since 1992 several lessons have been learned. The following are some conclusions from Lenton and Muller's (ibid.) analysis of IWRM theory and practice:

- Societies will use their own practices of governance to determine the appropriate balance between social, economic and environmental goals.

- The most important determinants, as well as outcomes, of better water management will usually be found outside the water sector

- There are no best solutions: optimizing economic growth, social equity and environmental sustainability implies that there will be compromises and trade-offs.

- Policy reforms and their implementation will only succeed if underpinned by a sound technical foundation

- Water resources planning and management must be linked to a country's overall sustainable development strategy and public administration framework

Implicitly, water productivity improvements are integral parts of these conclusions. In their analysis of integrated water resources management practices, Lenton and Muller (2009) conclude that "*Managing water effectively requires the sustained effort and engagement of women and men in all sectors of society if it is to be successful in achieving the society's goals*". In practice this requirement transforms into the need for participation of all stakeholders, competent institutions and sound investments in infrastructure.

The Comprehensive Assessment of Water Management in Agriculture (2007, p.283) considered water productivity at five different scales: crop, plant or

Table 3: Framework for investment opportunities to increase water productivity in agriculture

(After CA, 2007)

Scale of intervention	Water balance target	Investment required
1. Point/plant	1.1 Transpiration efficiency	Crop improvement Access to inputs
	1.2 Increase harvest index	Crop science Access to inputs
2. Field/farmer	2.1 Increase T/E ratio	Extension services Farmer field schools
	2.2 Alter rainfall partitioning	Conservation agriculture Soil-water conservation
3. Basin/system	3.1 Rainwater harvesting	IWRM (land-use planning) Watershed development
	3.2 Irrigation improvement (a) on-farm focus	Drip irrigation Deficit irrigation Supplemental irrigation
	(b) system focus	Improved supply delivery Improved rainfall response Wastewater re-use Drainage re-use

T = transpiration (productive use) ; E = evaporation (non-productive use); IWRM = Integrated Water Resources Management

animal; field or pond; farm or agricultural enterprise; irrigation system; basin and landscape. In order to define a framework for investment opportunities, scale is clearly important, but we propose to simplify the analysis and consider three different scales. To properly identify opportunities to improve water productivity at any of these scales it is essential to consider the main elements of the water balance. We therefore follow the Comprehensive Assessment (ibid. pages 286 and 326) in identifying potential targets for improvement. In each case we can thus identify investment opportunities as summarized below.

For identifying investment opportunities at basin or landscape scale we need to distinguish between irrigated and rainfed cropping systems (Table 3). Within rainfed systems the focus is on the adoption of measures to decrease non-productive flows and divert water to productive uses. Engineering measures to achieve this aim fall within the general description of rainwater harvesting. There have been successes in promoting rainwater harvesting innovations at a range of scales from on-farm micro-catchment systems to community scale macro-catchment systems in Sub-Saharan Africa (Malesu *et al* 2007 – Mapping the Potential of Rainwater Harvesting Technologies in Africa, ICRAF Technical Manual No 7) and many other regions. There is scope for further investment to promote up-scaling and out-scaling of these initiatives. Investments in integrated water resources management and in watershed development provide vehicles for delivering these improvements at landscape scale. Land-use planning may be part of the integrated resource allocation strategy as in the case of measures to control ‘streamflow reduction activities’ in South Africa. Incentive schemes (such as ‘working for water’ in South Africa) or compensation schemes as reviewed by Poras *et al* (2008) may be part of an investment package to improve rainfed systems.

Critically, water resources management should have mechanisms to allocate and govern the use of water that reflect the value of water in addressing the social and economic necessities of society. These mechanisms should encourage the efficient use of water where it is used for economic purposes (Lenton and Muller, 2009). Hence one of the challenges of economic water productivity is how to value and pay for environmental services that are largely supported by green water. Social water productivity has received less attention, but it has been reported that disregarding social values in allocation decisions causes market failure (Hellegers, 2006, quoted in Hellegers *et al*., 2009). Water allocation is essentially driven by political considerations in which social values play a minor role as they have rarely been quantified. Hellegers *et al*. (2009) developed a method that derives an implicit minimum social value on the basis of economic productivity losses. This socio-economic analysis quantifies the economic productivity losses of policy decisions. The authors demonstrate the usefulness of combining remote sensing and socio-economic analysis to assess variability in crop water productivity and economic water productivity. They used data from the Inkomati Basin in the eastern part of South Africa, where—according to the Water Act—water has to be reserved for basic human needs and to protect aquatic ecosystems. According to the authors, the justification for reallocating water between categories of users will be strengthened considerably and be more objective when the foregone benefits of allocating water in a more socially optimal way instead of in a more economically productive way are known. These opportunity costs can be interpreted as a kind of proxy of the minimum value society attaches to allocation water in an optimal way. The method can show the most cost-effective way of achieving that objective (Hellegers *et al*, 2009).

MESSAGE 9: TARGETED POLICY ACTIONS CAN SUPPORT INTEGRATED WATER AND LAND MANAGEMENT FOR IMPROVED WATER PRODUCTIVITY

To realize potential gains in water productivity it is necessary to address the policy context. Supporting measures can be enacted to enable water productivity enhancing interventions at the farm and watershed levels.

Closing the yield gap and improving water productivity is not just a matter of transferring better technologies to farmers, but of putting in place the institutional structures (e.g., markets, finance and risk management) that farmers need to adopt new technologies. For example, adoption rates of improved varieties (expressed as area planted with these varieties as portion of the total area planted with each of these crops) of rice, wheat, maize, sorghum and potatoes have been lowest in sub-Saharan Africa. Compared with South Asia, adoption rates for improved varieties of wheat have been fairly close (85 per cent and 70 per cent for South Asia and Sub-Saharan Africa, respectively), but adoption rates for improved rice varieties differed much more: 75 per cent in South Asia, and 23 per cent in sub-Saharan Africa (World Bank, 2007, p. 159). These differences illustrate the contrast between successful introduction of Green Revolution varieties and farming systems in much of Asia with the absence of it in Africa. Water productivity gains would be expected to follow similar trends.

National and local policies can be supportive or provide barriers and disincentives for the adoption of better practices by farmers. It is in governments' interest to support and stimulate the adoption of available technologies because they are likely to affect crop

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Institutional dimensions impact adoption of new technologies in Uganda

Household decision processes are important when new technologies to improve farm production are taken. A study from 450 households in Uganda reports on farmers' decisions regarding income strategies, participation in programs and organizations, crop choices, land management, and labor use, and their implications for agricultural production and soil erosion. It was found that government agricultural extension and training programs contributed to a higher value of crop production in the lowlands, but to soil erosion in the highlands. By contrast, programs by non-governmental organizations, programs that focused on agriculture and environment, helped to reduce erosion but had less favorable impacts on production in the lowlands. These findings confirm that many factors have context-specific impacts and involve trade-offs between increasing production and reducing land degradation. The impact of poverty on agricultural production was mixed and depended on the nature of poverty: smaller farms obtain higher yields per hectare, while households with fewer livestock have lower yields. In general, the results imply that the strategies to increase agricultural production and reduce land degradation must be location-specific, and that at a given context, there are only a few 'win-win' opportunities to simultaneously increase production and reduce land degradation.
(Pendera *et al*, 2004).

selection and livelihood choices and subsequently the productivity of land and water resources. Whether governments take notice probably depends on the extent to which they take cognisance of the possible adverse effects of water scarcity and climate change. According to Yohe *et al.* (2007), market signals are an essential factor in determining the necessary responses to a changing environment. But markets often involve significant time lags and overlook equity. Both these issues should be addressed in a risk management perspective, but Yohe *et al.* (ibid.) maintain that equity would provide the measure of success or failure. These authors distinguish several stages in public intervention in implementing adaptation measures and policies in response to climate change, including providing information, advice and training, promoting adaption measures, mandating adaptation, and institutionalizing adaptation capacity and policies.

Although these different degrees of government involvement probably apply equally well to the adoption of water productivity enhancing measures as to measures designed to adapt to climate change, the degree to which governments know what to do or to promote can be different. Yohe *et al.* (ibid.) suggest that the underlying determinants of a high capacity to adapt or to mitigate undesirable effects include sustained access to resources (i.e. water and land), strong social and human capital, and access to risk-spreading mechanisms, such as insurance against crop failure. The rural poor in Sub-Sahara Africa and South Asia are lacking in most of these factors most of the time. Whereas the effects of water scarcity are now being felt, the effects of climate change are not yet widely experienced. Nevertheless, IFPRI (2006) reported that 90 percent of farmers in South Africa's Limpopo basin have noticed increased temperatures and reduced rainfall levels over the past 20 years. Similar but lower figures were found for farmers in the Ethiopian Highlands. Dinar *et al.* (2008) report from extensive country-level surveys across Africa that large numbers of farmers already perceive that the climate has become hotter and that the rains have become less predictable and shorter in duration. According to some observers, fewer than half of the farmers who perceived long-term weather changes have implemented any changes in their farming practices. In all countries of the studies reported by Dinar *et al.* (ibid.), except Cameroon and South Africa, the planting of different varieties of the same crop and planting at different dates were considered to be the two most important adaption measures. The actual adaption process is driven by a number of factors. Experience and education of the farmers and the presence of extension advice are the most important aspects, but insufficient access to credit was identified as one of the key obstacles to adoption.

Most governments in Africa face tight budget constraints, making it difficult for governments to invest in supporting the adoption of better water and land management measures or adaptations to climate change. However, governments, donors, and development experts agree that agriculture is critical for reducing poverty and promoting economic development (e.g., WB, 2007). For instance, a study of 35 countries by Timmer (quoted in Runge *et al.*, 2003) found that a one percent increase in agricultural GDP led to a 1.6 percent increase in the per capita incomes of the poorest people. The two groups that make up the majority of the poor, peasant farmers and landless rural households, benefit directly through higher incomes from agricultural productivity gains brought about by research and new technology. In spite of the evidence, many constraints to improve agricultural production remain in place.

Weakness of governance is another key factor underlying Africa's low agricultural productivity and general poor performance in economic growth and poverty reduction (Booth, 2005). The author finds that development literature on Africa avoids mentioning the continent's political weakness. Much is said about the need for capacity building without asking why the post-independence investments did so little to put Africa on a sustained development path.

Governance problems are also a major reason why many recommendations in earlier World Development Reports on Agriculture could not be implemented (World Bank, 2007, chapter 11: 245-265). The authors of the 2008 Report see evidence that the political economy is changing in favor of using agriculture for development: "*Democratization and the rise of participatory policy making have increased the possibilities for small-holders and the rural poor to raise their political voice.*" In spite of this more optimistic tone, the Report also points out that agriculture because of its complexity and diversity makes special efforts necessary. Rural women still face particular challenges to make their voices heard.

ECONOMIC ASPECTS OF WATER PRODUCTIVITY

Economic dimensions of water productivity are as important as the agronomic and water management components. Water pricing has been considered by some to be a useful instrument that leads to more productive water use. In many countries, the price that farmers pay for water is much less than the value in industry and domestic use in urban areas. However, when all benefits of water use in agriculture at basin level are counted, the value of water is not as low as sometimes assumed (Hussain *et al*., 2007). Water pricing, if applied rigidly, leads to unacceptable consequences for poor farmers as well as for the urban poor. Water markets or market-like arrangements can be useful instruments in the efforts to achieve higher water productivity (Jury and Vaux, 2005). Markets work best in water-scarce areas if agriculture and water rights are well developed. In fact, the combination of self-reliance and established water rights tend to be found in areas of high water productivity. By now, the need for farmers' participation in the management of local water resources has been widely accepted. The adoption of measures to raise water productivity is much more likely when water management institutions are fully participatory and resources for infrastructure maintenance and long-term investments are available.

INVESTMENT AND COST FOR IMPROVED CROP AND WATER MANAGEMENT AT THE FARM SCALE

The investment cost per ha in World Bank funded irrigation projects (in Ethiopia) average about US$18,000, more than 13 times the South Asia average (AQUASTAT, 2008, quoted in Koohafkan and Stewart, 2008). This high figure is contentious, as others maintain that with the new generation of better-designed irrigation projects, costs in sub-Saharan Africa are now comparable to those in other regions. The World Development Report 2008 (page 65, World Bank, 2007) quotes an average figure of $8,347 per ha for the period 1995-1999, with an average economic return of 30 per cent. Other cost assessments suggest values of US$2,000 per ha for rehabilitation to US$5,000 per ha for new large scale irrigation in sub-Sahara Africa (Innocencio *et al*., 2005; Lankford, 2005) Corresponding values for South Asia are were circa 50 per cent of the sub Sahara Africa investment costs (Innocencio *et al*, 2005). However, it is worth noting that equivalent costs for small scale irrigation projects and so-called in-situ crop water management technologies have comparative values of US$50 to US$500 per ha converted (Noble *et al*, 2006;Kerr, 2002) depending on technology and location. As shown earlier, these technology improvements can hold substantial gains in water productivity, depending on yield response, especially when increasing yield levels from 1-2 t ha^{-1} to 3-4 t ha^{-1}, when the water productivity improvement can be in the order of 500-1000 m^3 per ton grain produced.

MARKET ISSUES

Governance problems tend to be more severe in countries where the economy is still largely based on agriculture, as is the case in most of sub-Saharan Africa (see Table 1). There the state is especially important for addressing market failures. Political and economic instability, limited accountability, low state capacity, corruption and poor rule of law make the problem worse.

Failing markets discourage farmers and producers from making the investments needed to improve crop yields and water productivity. Market imperfections reflected by high transaction and high transportation costs give famers' few economic incentives to adopt improved land management practices in the Iganga District of eastern Uganda (Woelcke, 2006). This is one of the conclusions from a bio-economic household study carried out in an area characterized by low input-low output systems. The development opportunities in the area are not being realized. Based on a farmer participatory research approach new production methods were introduced in the area with high agricultural potential, high market access, and high population density. Market imperfections are illustrated by the difference between consumer and farm prices for maize of about 40 per cent in neighboring Kenya, compared with a difference of about 500 per cent in Uganda. Another issue is the price of fertilizers. At the time of the study, the fertilizer market in Uganda is underdeveloped: there are few importers from Kenya, and the market suffers from outdated regulatory policies. If all of these were improved the price of fertilizers could be reduced by some 40 percent. In the meantime sustainable agricultural intensification is not profitable. The author states that only significant simultaneous changes in input and output prices would induce farm households to adopt new technologies and thereby improve household welfare and conserve soil nutrients (Woelcke, 2006).

INVESTMENT IN AGRICULTURAL WATER MANAGEMENT IN THE NILE BASIN: GAINS IN WATER PRODUCTIVITY

Water productivity gains can be associated with investments costs as in recent IMPACT model simulations (Sulser *et al* 2009 in Hoff *et al* 2009), which demonstrate the large potential for improving green and blue water use through targeted investments. Their Nile basin analysis for rainfed and irrigated cereals shows that under a "high investment" scenario, an increase in rainfed yields, crop water productivity and total production, goes along with a reduction in area expansion and consumptive water use, compared to the baseline scenario. The high investment (baseline) scenario assumes total annual investments in irrigated and rainfed agriculture of US$0.36 (0.23) billion for agricultural research, and US$0.44 (0.19) billion for rural roads across all Nile basin countries (including those parts of the countries that are outside of the Nile basin) until 2050. Annual investment in irrigation would be almost identical in the high investment and baseline scenario: US$0.11 versus US$ 0.12 billion.

Assuming a total Nile basin country agricultural area in the region of 25 million hectares, where about five million hectares are irrigated. The investment cost for the base line scenario is of the order of 0.42 billion US$ for about 20 million ha, equivalent to an investment cost of the order of US$1,680/ha Correspondingly, the high investment scenario is equivalent to to US$ 3,200 per ha. Thus, in this investment scenario, each hectare would need to double to realise a water productivity gain of nearly 840 m^3 per ton grain produced. Although this may be a costly investment, the additional benefits of good infrastructure such as roads, and better household food security and income (through increased yields) also need to be accounted for in a full benefit-cost estimate.

Moreover, under the high investment scenario, calorie availability, a proxy for food security, would improve (by 800 kcal per capita per day in 2050 on average) in the Nile basin countries as a result of higher food production and result in lower food prices, which would make food more affordable for the poor.

Table 4: Rainfed crop area, water use, yield, crop water productivity, and production for baseline and high investment scenarios in the Nile basin (After Sulser *et al* 2009 in Hoff *et al* 2009)

Scenario	rainfed crop area (1000 ha)	rainfed green water use (km^3)	rainfed yield (t/ha)	rainfed CWP (kg/m^3)	rainfed production (1000 t)
Baseline	13.04	78.14	1.64	0.27	21.41
high investment	12.12	72.47	2.06	0.35	24.96

MESSAGE 10: CAPACITY BUILDING AND AWARENESS IS ESSENTIAL

CAPACITY BUILDING AND AWARENESS RAISING

In many areas where increases in water productivity are needed, knowledge exists, but institutional capacity and human capital are inadequate to support the knowledge transfer needed to accelerate the adoption of new technologies that lead to increased yields and water productivity. In such cases, the top-down approach to technology transfer is not effective and should be changed into a participatory approach combining traditional knowledge with scientific technology (Lal, 2007a). Echoing the sentiments expressed by Borlaug (2002), Lal (2007b) emphasizes the importance of using modern and innovative technologies. In the context of improving agriculture in sub-Saharan Africa, Lal (ibid.) refers to the Law of Marginality. It statesthat “marginal soils cultivated with marginal inputs produce marginal yields, support marginal living, and create a marginal environment prone to physical, social, and economic instability”. According to Lal (2007b) “ *With the world population expected to increase from 6.6 billion in 2007 to eight billion in 2020, there is no choice but to use cutting-edge science, including (..) biotechnology (..) and knowledge management*” to enhance agricultural production in sub-Saharan Africa”.

Human capital will need strengthening at several levels to meet the potentials of water productivity improvements due to yield gaps and inefficient water and land management. At the farm level, knowledge transfer is required for upgrading crop and livestock production with known technologies. Extension systems require support for capacity building to enable them to deliver locally appropriate advice based on proper problem diagnosis. Given the nature of the technical innovations involved, there is scope for dissemination through farmer field schools as an alternative to conventional extension mechanisms.

At the landscape management scale, water and land resource managers will need to integrate both green and blue water flows to address multiple demands and potentials. Instead of bypassing rainfed agriculture, there is a need to identify opportunities and gains through investments in these areas, as they hold the largest potential for water productivity improvements and yield increases (CA, 2007, p.317). This paradigm shift in water and land resource management is a great step from the conventional ‘blue water approach’ on which many resource managers have been taught.

At national and international level, awareness about policy implications of trade, subsidies and investments in all levels of education can impact on how water productivity is assessed from farm to watershed/basin scales.

The need for investment in human and institutional capacity is critical to addressing current development

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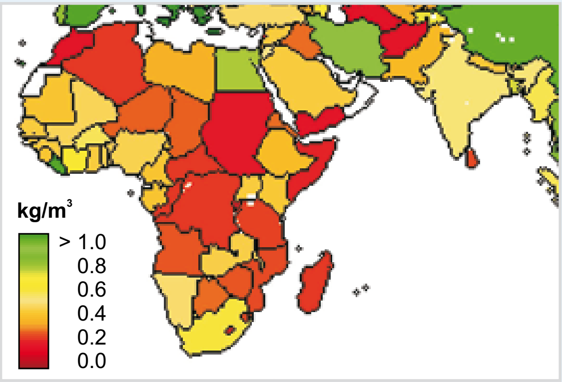
Climate change and potential impact on water productivity

Climate change will, with current predictions on change in rainfall patterns and increasing temperatures, slightly decrease water productivity for maize in sub-Sahara Africa and South Asia, unless active measures are taken to adapt and improve water productivity. A recent estimation using LPJ modeling for maize in 2040-to 2070, suggest that there will not be any climatic 'natural' opportunities to gain in water productivity. In addition, population will increase and there will more likely be an increased demand on water resources from other uses than food production. To meet development targets on hunger and poverty alleviation, and sustainable development, water productivity improvements will be a key path to improve water use and secure agricultural productivity for growth and development.



(After Fader *et al*, in review)

issues as well as future constraints such as water management in a changing climate. Africa is likely to be the hardest hit by the impacts of global warming. Some models indicate that temperature increases in parts of Africa could be double the global average increase (IFPRI Forum, December 2006, Dinar *et al*., 2008). The reason for Africa's particular vulnerability to climate change is the high proportion of low-input, rainfed agriculture compared to Asia and Latin America. Rainfall variability is higher in Africa than anywhere else and is expected to get even more erratic because of global warming. Livestock production, which in Africa depends mostly on range and grassland, is subject to the same high rainfall variability as rainfed crop production, and the impacts of climate change. Africa depends heavily on agriculture, which employs some 70 percent of the people, and the effects of climate change could put millions of people at greater risk of poverty and hunger.

According to the November 2006 report from the United Nations Framework Convention on Climate Change (quoted in IFPRI, 2006), climate models show that 80,000 km^2 of agricultural land in sub-Saharan Africa that is currently classified as water constrained will experience more rainfall with climate change. But a much larger 600,000 km^2 that are classified as moderately water constrained will become severely water limited. More recent information indicates that climate change is expected to be more serious now CO_2 emissions have risen in recent years (annual rate of emissions 0.9 percent from 1990 to 1999 versus 3.5 percent since 2000, according to Dr. C. Field, one of the IPCC members, in a recent lecture to the American Association for the Advancement of Science. http://www.scidev.net/en/news 17 February 2009).

ACKNOWLEDGEMENTS

We thank the co-authors Dr Suhas P. Wani, ICRISAT, Dr Dennis Wichelns, Indiana University Northwets , and Mr John Gowing, University of Newcastle for their contributions. A special thank you to Sander Zwart, WaterWatch (NL) who provided the water productivity data for rice from the meta-analysis by Zwart and Bastiaanssen (2004). The contribution of WP map for climatic change scenario was kindly provided by Ms Marianela Fader, Potsdam Institute of Climate Impact Research. This report was funded by the Swedish Ministry of Environment.

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