21 Assessing and Improving Water Productivity of Irrigated Rice Systems in Africa

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Introduction

Fresh water resources are becoming increasingly scarce in many parts of the world (Molden, 2007). Africa, however, is endowed with large available fresh water resources. It is estimated that total water available from rivers, lakes and wetlands on the continent amount to 31,766 km^3, which is more than Asia and North America, and total groundwater resources are estimated at 5.5 million km^3 (WRI, 2005). However, the sources are unevenly distributed across the continent and its agroecosystems. In large areas of North Africa overexploitation of ground and surface water is common. Many river basins in Egypt, Libya, Tunisia, Algeria and Morocco are classified as heavily exploited or overexploited (UNEP, 2008; FAO, 2011) and consequently fresh water is scarce (less than 1000 m^3 per person per year). Across sub-Saharan Africa (SSA), available fresh water resources per capita average 6322 m^3, but vary from 508 m^3 in Burundi to 218,000 m^3 in Congo (UNEP, 2008).

The agricultural sector is the largest consumer of fresh water resources. In SSA, approximately 88% of total annual water withdrawals in 2000 were destined for agriculture, 4% for industry and 9% for domestic use (WRI, 2005). In general, SSA river basins are still able to supply sufficient water for drinking water and irrigation. Exceptions are the Volta River basin in West Africa and the Orange and Limpopo River basins in Southern Africa, where population density and large-scale irrigation systems put great strains on water resources availability (Ravenga *et al.*, 2000).

There is large untapped irrigation potential in SSA. IFPRI (2010) estimates that the largest potential for small- and large-scale irrigation systems is in Nigeria (5.7 million ha). For SSA as a whole, this potential amounts to 21 million ha, of which the Gulf of Guinea sub-region has almost 50% (10 million ha). However, efforts to manage water and to make it available (e.g. for agriculture) are hindered by the undeveloped state of institutions in terms of low levels of expertise, knowledge and capacity to develop and manage irrigation, and by the prevalence of subsistence farming. Other challenges for development are related to the absence of an adequate policy and strategic framework, the often disappointing results of previous irrigation development, the need for continued support to cover recurrent costs from the public sector, and the relatively high costs of conventional irrigation development (IFPRI, 2010).

The agricultural sector faces increased competition from other users, such as the industrial

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and domestic sectors. Due to growing demand for water resources from all sectors, it is projected that by 2025, some 13 countries in SSA (including Nigeria, Ghana and Madagascar) will face water stress (less than 1700 m^3 per capita per year) and another 10 countries (including Egypt, Malawi and Rwanda) will suffer from water scarcity (less than 1000 m^3 per capita per year) (UNEP, 2008). Countries that are currently on the safe side may face water stress in the future.

Water stress will be exacerbated by the impacts of climate change, which will have a large impact on river-basin hydrology. Sub-Saharan Africa is particularly vulnerable to the impacts of climate change (IPCC, 2007). Water availability from rainfall and rivers will decrease in many river basins as rainfall and runoff decline, while the evaporative demand will increase due to predicted elevated temperatures (e.g. Jackson *et al*. 2001; Smakhtin *et al*., 2004; De Wit and Stankiewicz, 2006). Large areas in West Africa (Senegal River basin), North Africa (Morocco, Algeria, Tunisia) and Southern Africa (e.g. South Africa, Botswana) are projected to suffer an increase of 20% or more in water shortage by 2050 (measured in cubic metres of water per capita). On the other hand, the Nile River basin seems likely to benefit from changes in climate and increased water availability is foreseen (Arnell, 2004).

The increasing population, together with the anticipated impacts of climate change and expansion of irrigated areas, are putting pressure on water availability for African agriculture. Decreasing availability of water in SSA threatens the sustained realization of current levels of rice production in irrigated systems and will affect the food security and livelihoods of many. It is within this context that African agriculture has to become more efficient in the use of water to sustain and where possible enhance food production. It is therefore inevitable that agriculture, being the largest consumer of water, must make the largest gains in productive use of water resources (Molden, 2007).

Rice production is often claimed to be the largest consumer of water in an agricultural context. However, this depends on the definition of water use and the scale at which it is considered. Certainly, rice is the largest consumer of fresh water resources when we consider irrigation water supplies diverted to a single field. In irrigated rice systems, significant volumes of water are used for land preparation and farmers keep fields continuously inundated during the growing season (Bouman *et al*., 2007). The water productivity, defined as the crop yield divided by the total water applied by irrigation (WP_I), at field level is generally low because of the water needed for land preparation and losses to seepage and lateral flow. The variation in magnitude in applied irrigation water is high and varies between fields and systems due to differences in land preparation (direct seeding or transplanting, puddling of soil), water management and variations in environmental conditions such as soil type and groundwater levels.

However, if we place the rice field in the context of an irrigation system or a river basin, the situation changes. The excess water that has not evaporated, transpired or percolated to depths where it can no longer be retrieved, will return to the system where it is available for re-use (Seckler, 1996). WP_I can be calculated for individual rice fields, but also at the level of irrigation systems or administrative units within the systems. At higher levels, the WP_I is expected to improve due to the re-use of ‘lost’ water from groundwater and drainage effluents. The best example is Egypt’s Nile River delta: only a small share of total water discharge is effectively released into the Mediterranean Sea, because water is re-used several times to irrigate rice and other crops.

In the context of the water-scarcity debate that has evolved, the importance of evapotranspiration (the combination of transpiration from plants and evaporation from soil and water) has been acknowledged. Evapotranspiration – along with pollution and deep drainage – represents the water that is really lost from a basin and is not available for re-use in productive processes. Saving water by reducing evaporation during the growing season is therefore considered a real water saving, since more water will remain available for other uses within a river basin. Reducing the amount of irrigation water applied to a rice field will only save water from a river basin perspective if this water would otherwise be lost for re-use. For example, in the case of the Office du Niger irrigation scheme (Mali), drainage water is not re-used and cannot return to the Niger River; drainage water evaporates or flows to deeper groundwater layers and is, therefore, lost for re-use.

A review of 13 experiments found that evapotranspiration in irrigated rice varies from 400 mm to 800 mm seasonally (Zwart and Bastiaanssen, 2004). This is high compared to crops such as wheat (200–500 mm), but not compared to cotton (400–900 mm) or maize (200–1000 mm). If water productivity, defined as yield divided by the amount of water consumed by evapotranspiration (WP_{ET}), of rice is compared to other major crops, only maize has significantly higher values (1.1–2.7 kg/m^3) as it is a C_4 crop. The range of water productivity of rice is more or less equal to that of wheat: 0.6–1.6 kg/m^3 (Bouman and Tuong, 2001; Zwart and Bastiaanssen, 2004).

This chapter provides an overview of water productivity of irrigated rice at field and scheme levels in Africa based on a literature survey; reviews studies on assessment of water productivity at field and scheme levels for irrigated rice in Senegal and Mali; and ends with recommendations for improving the productive use of scarce water resources for rice production, and for further research.

Water Productivity in Rice in Africa: An Overview

A literature review was conducted to assess the levels of water productivity of rice by synthesizing the results of experimental trials and regional studies that have been conducted throughout Africa (Table 21.1). Two definitions of water productivity were considered: (i) rice yield divided by seasonal evapotranspiration (WP_{ET}), and (ii) yields divided by total water input from irrigation and precipitation (WP_I). Results from field experiments and (remote-sensing) modelling were included. All the studies are related to irrigated rice systems whether in SSA (Senegal, Nigeria, Ghana, Mali, Burkina Faso) or North Africa (Morocco, Egypt). We did not find any study on water productivity related to rainfed rice or any crop-modelling studies on rice water productivity on the African continent. In the reported studies, WP_{ET} values are higher in Egypt (1.25–1.65 kg/m^3) than in SSA countries, where WP_{ET} remains well below 1.0 kg/m^3. Yields in Egypt are among the highest in the world due to extremely favourable growing conditions. However, the values for WP_{ET} measured in Egypt are comparable with the global average of 1.1 kg/m^3 that was based on a review of 13 publications. The levels of water productivity under SSA conditions appear well below the world average levels (Zwart and Bastiaanssen, 2004).

High values of WP_{ET} in one country do not necessarily mean that others are performing below their potential. There are many reasons, including climate and soils, which cause variation in water productivity from country to country or from region to region, and these are not manageable by human intervention (Dawe, 2005). Comparing water productivity between different experiments must therefore be conducted with extreme caution and non-manageable factors must be excluded. For example, the high values obtained in Egypt must not be set as a benchmark value for a rainfed rice system in Togo, rather local optimal values of water productivity must be used.

Assessment and Improvement of Water Productivity of Rice at Field Level

The most direct way to raise water productivity in irrigated rice cropping in Africa is to improve crop management in general. Yields per unit of land or per unit of water consumed by evapotranspiration (expressed as WP_{ET}) or irrigation water applied (WP_I) are still far below what would be possible with improved management. It is also possible to increase water productivity, expressed as yield per unit of water applied (WP_I), by reducing the application of irrigation water during the growing season for land preparation and growth of the rice crop. However, it then becomes important to maintain rice yields. One option to reduce water intake at field level (and thus improve WP_I) is the practice of intermittent flooding or alternate wetting and drying (AWD). Rice is grown without a permanent layer of standing water on the field, and irrigation water is applied to obtain flooded conditions after a certain time has passed after the disappearance of ponded water (Bouman *et al.*, 2007). Bouman and Tuong (2001) report that such practices can reduce irrigation water input while maintaining rice production.

Table 21.1. Levels of water productivity in African countries.

Definition[a]	Method	Condition	WP range (kg/m^3)	Location and country	Years	Source
Y/ET	Field experiments	Irrigated	0.53–0.64	Ndiaye and Pont-Gendarme, Senegal	1990	Raes *et al.* (1992)
Y/ET	Field experiments	Irrigated	0.50–0.79	Kadawa, Nigeria	1991–1992	Nwadukwe and Chude (1998)
Y/ET	Regional estimate	Irrigated	0.56	Tono, Ghana	2005–2006	Mdemu *et al.* (2009)
Y/ET	Field experiments	Irrigated	0.93–1.01	Nile delta, Egypt	Not given	Kheira (2009)
Y/ET	Remote sensing	Irrigated	1.25–1.65	Nile delta, Egypt	2006	Zwart and Bastiaanssen (2007)
Y/ET	Remote sensing	Irrigated	0.53–1.03	Office du Niger, Mali	2005	Zwart and Leclert (2010)
Y/ET	Literature review	Irrigated	0.6–1.6	Globally	1979–2004	Zwart and Bastiaanssen (2004)
Y/(I+P)	Field experiments	Irrigated	0.23–1.28	Ndiaye and Fanaye, Senegal	2005–2006	De Vries *et al.* (2010)
Y/(I+P)	Field experiments	Irrigated	0.27–1.07	Fanaye, Senegal	2007	Krupnik *et al.* (2012a)
Y/(I+P)	Field experiments	Irrigated	0.22–1.43	Ndiaye, Senegal	2008	Schlegel (2010)
Y/(I+P)	Field experiments	Irrigated	0.34–0.88	Gorgo, Mogtedo & Itenga, Burkina Faso	1993–1994	Dembélé *et al.* (2001)
Y/I[b]	Field experiments	Irrigated	0.60–1.17	Kafr El-Sheikh, North Delta, Egypt	2006–2007	El-Bably *et al.* (2008)
Y/I[b]	Field experiments	Irrigated	0.52–0.99	Giza, Egypt	Not given	Nour *et al.* (1997)
Y/I[b]	Field experiments	Irrigated	0.50–0.80	Gharb, Morocco	1995–1997	Lage *et al.* (2004)

[a]Y = rice yield, ET = evapotranspiration, I = irrigation water deliveries, P = precipitation.
[b]In these studies the contribution of water from precipitation was nil or close to nil.

In Senegal, Africa Rice Center (AfricaRice) conducted water-saving experiments in irrigated rice schemes in the Senegal River valley (De Vries *et al.*, 2010; Krupnik *et al.*, 2012a). The specific objective of the study by De Vries *et al.* (2010) was to test the possibility of saving water in rice production in a Sahelian environment by quantifying the effects of different water regimes on rice yield and irrigation water productivity under weed-free conditions with ample nitrogen. Five field trials were conducted in 2005 (dry season, DS2005, and wet season, WS2005) and 2006 (dry season, DS2006) at two research stations – Ndiaye (delta, 16°11′N, 16°15′W) and Fanaye (middle valley, 16°32′N, 15°11′W). The experiment in DS2005 was only conducted at Ndiaye. Irrigation was measured at inlets at the entrance of the field; rice yield, irrigation water delivery and irrigation water productivity (WP_I) were determined for four irrigation regimes: alternate wetting and drying (AWD) throughout the season; AWD until panicle initiation and the rest of the season flooded (AWD-flooded); flooded until panicle initiation followed by AWD (flooded-AWD);

and continuously flooded throughout the season (flooded). Weeds were controlled at 21 days after sowing, and N was applied at the recommended rate of 150 kg/ha (see the publications for complete details of the experiment).

The amount of irrigation water used across all trials ranged from 480 mm in the AWD treatment during WS2005 in Ndiaye to 1490 mm in the flooded treatment during DS2005 in Ndiaye.

Rice yields ranged from 2.3 t/ha to 11.8 t/ha in the water-saving treatments. They ranged from 3.7 t/ha to 11.7 t/ha in the flooded treatments. In the wet season, the treatments in which AWD was applied during part of the season resulted in the highest yields at both sites. In the dry season, the continuously flooded treatment out-yielded other treatments, with the exception of AWD in Fanaye. At the particularly weed-infested Ndiaye site, the control of weeds increased yields from an average of 2.0 t/ha to 7.4 t/ha in the dry season and from 1.4 t/ha to 4.9 t/ha in the wet season. No weed control in combination with AWD during the vegetative stage reduced yields to below 1.0 t/ha. However, when weeds were controlled, crop yields obtained with a combination of AWD and flooding were comparable with those obtained in fully flooded plots receiving the same weed management treatment.

These results demonstrate that it is possible to attain major savings of irrigation water with little loss of yield in a Sahelian environment: during the wet season, irrigation water savings of 22–39% are possible for rice with no or little yield loss, while maintaining high water productivity. An important pre-condition, however, is good weed control and the application of sufficient mineral fertilizer.

Krupnik *et al.* (2012a) compared recommended farming practices (RFP) against an adapted form of the System of Rice Intensification (SRI) in two regions of the Senegal River valley (delta and middle valley). SRI is claimed as a means for saving water in rice systems, and in the Sahel it has been tested in The Gambia (Ceesay, 2010) and Mali (Styger *et al.*, 2010). Experiments were laid out according to a split-split-plot design that allowed evaluation of rice yields, weed competition, water savings and water productivity in both SRI and RFP. In RFP, a continuous floodwater layer was maintained in the fields until 2 weeks before harvest, whereas in SRI the system of AWD was applied in which a shallow water layer (2–3 cm depth) was reapplied only when the soil surface had begun to dry and hairline cracks became visible (no more than twice a week). Two weed management treatments, weedy and weed-free, were implemented. A full description of the experimental layout and the measurements is provided by Krupnik *et al.* (2012a).

Two major conclusions stem from this work. First (and this confirms previous claims), substantial field-level water savings and significant increases in water productivity can be obtained with SRI compared to RFP, through AWD practices. Table 21.2 shows that in both locations and for both seasons SRI resulted in higher values of WP_I than RFP under weed-free conditions. For example, in the delta area average WP_I for SRI was 0.74 kg/m^3 and 0.81 kg/m^3 in the dry and wet seasons, respectively, while WP_I for RFP was 0.60 kg/m^3 and 0.64 kg/m^3. The second major conclusion is that the positive impact of SRI on water productivity only holds when weeds are adequately controlled. When subject to weed

Table 21.2. Main effects on water productivity (WP_I in kg/m^3) for each crop management system and across sites and seasons. (Adapted from Krupnik *et al.*, 2012a.)

Water management	Senegal River delta				Senegal River middle valley			
	Dry season 2008		Wet season 2008		Dry season 2008		Wet season 2009	
	Weed-free	Weedy	Weed-free	Weedy	Weed-free	Weedy	Weed-free	Weedy
Recommended Farmer Practice	0.60b	0.34a	0.64b	0.42b	0.43b	0.23a	0.73b	0.70b
System of Rice Intensification	0.74a	0.22b	0.81a	0.35a	0.53a	0.25a	1.31a	0.95a

Values in a column sharing the same letter are not significantly different according to the least-significant means T-test (α=0.05).

competition, weed growth was consistently greater under SRI than RFP, in both the dry and wet seasons. Yield losses in the SRI trials without proper weed management were greater than in the RFP in the majority of cases. If farmers have sufficient resources to control weeds and fields are well-levelled, 'SRI-type water management' can, therefore, support water saving in rice-based systems.

These examples show the importance of keeping a close eye on crop management in general for enhancing water productivity in rice fields in Africa if attempts are made to reduce irrigation inputs at field level.

When trying to improve water productivity, the scale as well as its definition needs to be considered in order to ensure that the desired impact is achieved. Improving water productivity at field scale by reducing the water applications may not necessarily contribute to overall water productivity enhancement of an irrigation system. Often water is recovered and re-used by placing check dams or by pumping groundwater, and the impact of reducing water application may be much smaller than anticipated (Hafeez *et al.*, 2007). On the other hand, if a farmer aims at improving the benefit from his or her fields by reducing the cost of water, then reducing irrigation water applications may improve water productivity. Thus, farmers who use pumps to get water to their fields from either groundwater or rivers, and farmers who pay for water by volume may have an incentive to improve and optimize the water productivity in their fields. A practical way to implement AWD for increasing the water productivity is to monitor the depth of the water table in the field using a piezometer, or a simple perforated water tube placed inside the rice field. After an irrigation application the water depth will gradually decrease. When the water level reaches more than 15 cm below the soil surface, irrigation must be applied again to flood the soil with a depth of around 5 cm (IRRI, 2012).

Assessment of Water Productivity of Rice in a Large-scale Irrigation System Using Remote-sensing Techniques

The Office du Niger, situated in the Ségou region of Mali (13.7–14.9°N, 5.3–6.3°W), is one of the oldest and largest irrigation schemes in West Africa. It was originally intended as a large-scale cotton system, but today rice is cultivated on 99% of the land. The management of the irrigation system is sub-divided into five zones, of which Macina is the only one located along the Niger River (Plate 13 inset). The water for irrigation is diverted from the Niger River at the Markala dam and then flows into two former river branches from where the water is supplied to the fields through a hierarchical network of canals (Ertsen, 2006). Water is abundantly available to irrigators during the main cropping season and fields are likely to be overirrigated causing issues with waterlogging and drainage. Measurements of water supply to fields show large differences ranging from 8 m^3/ha to 30 m^3/ha per season (Vandersypen *et al.*, 2006). Future trends suggest that less water will be available for irrigation due to an expansion of the system, as well as reduced discharges in the Niger River and higher demands induced by climate change. There is a need to improve the irrigation performance in the Office du Niger in order to expand the system and sustainably provide water to the water users.

Irrigation performance assessment is considered an important management tool to implement, monitor and evaluate activities for water delivery services (Molden *et al.*, 2001). These assessments can focus on physical performance indicators as well as economic and institutional performance indicators. In this section, focus is on physical performance indicators.

Inputs that are required to assess the physical irrigation performance include measurements of different terms of the water balance such as discharge, evapotranspiration, effective precipitation, as well as measurements of crop yields, and estimates of irrigated area and cropping intensities. The application of indicators at the lower scale in an irrigation system, such as tertiary units, requires expensive and labour-intensive field campaigns (Vandersypen *et al.*, 2006). Moreover, it is virtually impossible to obtain a data set that systematically covers the whole system. This limits the possibilities for analysing, for example, the equity of water distribution among users in different parts of the system. The possibilities of using spatial remote-sensing data have been investigated (see Bastiaanssen and Bos, 1999, for a review).

Major advantages of remote-sensing-derived data over field-measured data are that they are objective, collected systematically and system-wide, and the information can be analysed at different scales (Bastiaanssen *et al.*, 2000).

A remote-sensing-based study was performed to analyse the irrigation performance of the Office du Niger irrigation system (Zwart and Leclert, 2010). The indicators assessed were water productivity (WP_{ET}), defined as the crop production divided by the seasonal water consumption from evaporation (kg/m^3), and the head–tail performance indicator (%). The latter is used to assess the uniformity of water distribution across the irrigation system or a sub-unit by assessing the spatial pattern of water consumption, rice yields and water productivity among irrigators in head and tail reaches of an irrigation unit or the entire system. Often, farmers close to the inlet of the system (head end) have better access to water, while irrigation water may fail to reach the irrigators near the tail end of a canal due to poor condition of control structures, illegal water use by irrigators upstream, or poor irrigation management.

The Surface Energy Balance Algorithm for Land (SEBAL) model (Bastiaanssen *et al.*, 1998) was developed to estimate the components of the surface energy balance, and thus the actual evapotranspiration, spatially from remote-sensing images and standard meteorological measurements (air temperature, wind speed, relative humidity and solar radiation). Remote-sensing images are used to calculate the Normalized Difference Vegetation Index (NDVI), the surface reflection and the surface temperature, which are inputs for the model. The model is equipped with a module to estimate biomass production spatially from the same images (Bastiaanssen and Ali, 2003). For this study, high-resolution Landsat images were used to produce detailed maps of estimated rice yield, seasonal water consumption and water productivity, from which the indicators were evaluated. The head–tail differences were assessed for the entire system, excluding the Macina zone. This area located in the former river bed was divided into 10 areas of equal size starting from the first irrigation water intake (head end) until the end of the system (tail end). The average yield, evapotranspiration and water productivity were calculated for each of the 10 areas (see Zwart and Leclert, 2010, for a full description of the methodology and the inputs used).

The average WP_{ET} in the 82,666 ha of rice cultivated in the Office du Niger during 2006 season was 0.78 kg/m^3, with a standard deviation of 0.12 kg/m^3. Certain areas in the system showed significantly higher water productivity, with values of up to 1.1 kg/m^3 (the blue and black areas in Plate 13). The zones of Macina and Kouroumari had lower average values (0.72 kg/m^3 and 0.75 kg/m^3, respectively) than the zones of Niono (0.83 kg/m^3), Molodo (0.81 kg/m^3) and N'Débougou (0.78 kg/m^3). However, the system average was low compared to the global range for water productivity of rice of 0.6–1.6 kg/m^3 (based on the experimental results of 13 sources worldwide; Zwart and Bastiaanssen, 2004). Slightly lower values (0.53–0.64 kg/m^3) were measured in a rice-based system in Senegal (Raes *et al.*, 1992); in Nigeria, water productivities for rice were in the range 0.50–0.79 kg/m^3 (Nwadukwe and Chude, 1998).

Significant differences were found in water consumption and estimated yields between the head and tail ends of the system (excluding Macina) (Fig. 21.1). Average water consumption amounted to approximately 780 mm per season at the head end of the system, but was 5% lower at the tail end of the system (743 mm per season). However, estimated rice yields at the tail end were 18% lower (5.4 t/ha compared to 6.5 t/ha at the head end). It was suggested by the irrigation managers that lower water quality and higher groundwater levels towards the tail end of the system could have been responsible for the lower yields. A potential limitation in the application of the model is the use of a fixed harvest index to estimate the crop yields from season biomass, as biomass estimation may be biased if fields are affected by weeds.

The low average water productivity throughout the Office du Niger (0.78 kg/m^3) and decreasing rice yields towards the tail end of the system (−18%) show that there is scope for improvement in the productive use of water resources. Remote-sensing data provided new insights into patterns of rice yields and water productivity. Remote sensing can further support the management of the system in strategic planning of water sources and in monitoring and evaluating where water resources are beneficially used and where water resources are wasted.

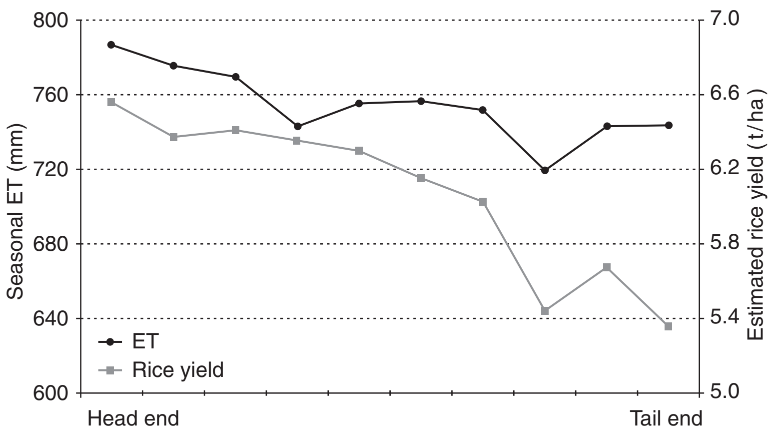

Fig. 21.1. The average seasonal water consumption from evapotranspiration and estimated rice yields in the wet season for the head and tail ends and eight areas in between in the Office du Niger, Mali. The assessment was made for the entire system, excluding the Macina zone (which receives water from a different canal). The distance between the head and tail of the system is approximately 100 km. (Adapted from Zwart and Leclert, 2010.)

By combining these data into existing data sets, the causes of low productivity can be researched and appropriate interventions can be developed. Other indicators can also be spatially analysed, so that water consumption and crop yields can be related to irrigation water supply: examples are cropping intensity, irrigation efficiency, and relative water supply (Bastiaanssen and Bos, 1999).

Conclusions

Africa is claimed to have abundant water and land resources, which would potentially allow the continent to expand its agricultural areas, increase food production and feed its own population. While on a continental scale this statement may hold true, on a regional scale large differences exist in availability of water resources for agriculture as the result of socio-economic and natural conditions.

Physical water shortages already exist in many river basins in Africa (e.g. the basins of the Volta, Orange and Limpopo rivers, and many smaller basins in North Africa) and the situation is likely to get worse (Arnell, 2004; Smakhtin *et al.*, 2004; De Wit and Stankiewicz, 2006). Climate change predictions show that in several regions the physical water availability will decrease significantly due to changes in rainfall, runoff and evapotranspiration. All countries in North Africa are already water scarce, while in SSA a total of 23 countries that are currently on the safe side will become either water stressed or water scarce in the near future (by 2025) as a result of population pressure and climate change effects. Projected water scarce or stressed countries by 2025 include the major rice-producing countries in Africa: Nigeria, Egypt and Madagascar (UNEP, 2008).

Less water will be available in future rice-farming environments in many regions. This will affect all rice-growing environments, including uplands, rainfed lowlands and irrigated rice systems. Spells of drought will occur more frequently and may become longer. Changing precipitation patterns will affect runoff and alter the hydrological regime of rivers and streams reducing river flows, increasing peak flows, shortening the period of water availability, and making the arrival of the peak discharges earlier or later. Rice farmers need to adjust their farming systems to the greater uncertainties and reduced supply of water from irrigation and rainfall in order not to become vulnerable to crop failure. Water-saving regimes, rainwater harvesting and drought-resistant varieties with shorter growing cycles are options that farmers can choose from.

Tools are being developed to enable farmers and irrigation managers to be more productive with scarce water resources and resilient to water scarcity. The field-scale studies in the Senegal River valley by De Vries *et al.* (2010) and Krupnik *et al.* (2012a) show that irrigation water supply can be reduced with limited yield penalties. Thus, the water productivity of rice (WP_I) can be improved by adopting new ways of managing irrigation water through SRI or AWD. Farmers can make significant water savings, but only when field management is optimal. Without proper weed management, such water-saving techniques may even have an adverse effect on water productivity and crop yields. The adoptability of SRI, which also requires land levelling and high nutrient inputs, is therefore believed to be low in SSA, since farmers have poor access to credit and markets (Krupnik *et al.*, 2012a). However, promising results were found where in a participatory on-farm experiment farmer-optimized practices (based on a selection by farmers of components of SRI and RFP) were evaluated (Krupnik *et al.*, 2012b). The on-farm evaluation revealed similar yields to RFP and SRI, but higher benefits due to different weed management. This confirms that simple blueprints that work in one place cannot simply be applied in another region without adjustments to the new situation.

The regional case study in Mali showed the large variation of water productivity (WP_{ET}) and yields that exists throughout an irrigation system. The variation is high between fields, but also between irrigation management units such as zones and tertiary units. Units close to the water inlet of the system outperform units at the tail end of the system. The remote-sensing analysis showed that improvements are possible and provides a valuable tool for irrigation managers to locate underperforming areas. However, it does not provide information on the underlying causes of high or low performance. Additional analysis on, for example, water quality, groundwater levels and water supply to irrigation units, must be conducted to pinpoint the causes of underperformance and to propose measures to improve yields and make the use of the water resources more productive. Spatial analysis in a GIS by combining remote-sensing-obtained data on crop yield and evapotranspiration with field measurements of (e.g.) water deliveries and groundwater levels in piezometers is an essential tool for such a purpose. Once such analysis is performed, measures can be targeted to specific locations. If, for example, the saline groundwater quality is an issue, salt-tolerant rice varieties can be introduced. Other management measures could include constructing and rehabilitating drainage systems, reducing water supply to match the demand, and taking land out of production.

In the case of the Office du Niger, farmers themselves have limited incentives to reduce water supply to their fields; yields are relatively high and they pay a fixed amount per season to irrigate their fields. Moreover, salinity is a serious issue and high water inputs ensure that salt is leached out of the root zone. However, waterlogging and limited drainage possibilities at the end of the season cause significant postharvest losses. The introduction of water-saving measures may be feasible, but it requires an in-depth analysis of possible effects on soil quality.

Potential tools for improving the productive use of scarce water resources have been identified, but need further research. Salinity and soil degradation are important issues in irrigation systems in the Sahel, and the effects of water-saving techniques must be investigated. In the case of the Senegal River valley, water is directly pumped from the river. Given high fuel prices, farmers and irrigation managers have concrete incentives to reduce water application to fields and increase profitability. However, in the case of the Office du Niger, a gravity-based system, farmers pay a fixed amount ('*redevance*') that permits them to irrigate during one season. Unlike systems with volumetric water pricing or pumps, there is no incentive for farmers to reduce water use; instead farmers will utilize all water available.

New research is proposed for irrigated rice systems focusing on testing promising water-saving techniques, such as intermittent irrigation, AWD and SRI, under a large range of conditions that prevail in Africa and including long-term effects on soils. The major challenge for research related to water-saving technologies will be creating impact and ensuring that tools meet farmers' needs. The right incentives must be created for farmers and irrigation managers to improve water management and sustain or improve productive use of water resources. On-farm participatory experiments are essential to optimize and improve a technology and to investigate the profitability and socio-economic constraints of proposed products and services. The impact pathways require high involvement of the stakeholders through an inter-disciplinary and participatory research process, which involves the farmers, as well as irrigation managers, development organizations and NGOs. Research must not only be implemented in experimental plots, but also in farmers' fields and irrigation blocks and schemes to assess the opportunities and limitations of water-saving options at different scales.

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