Chapter 3

Water use efficiency in agriculture: Measurement, current situation and trends

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Abstract

Agriculture is the largest consumer of water and total evapotranspiration from global agricultural land could double in next 50 years if trends in food consumption and current practices of production continue. There is an imminent need to improve the water use efficiency or more importantly the water productivity. This chapter explains in detail the concept and measurement of 'water-use efficiency' and 'water productivity' as applied at plant, field, farm, region/sub-basin, basin and national level through traditional and remote sensing based estimations. Further, the methods for improving water productivity under irrigated, water scarce conditions, paddy fields and large river basins are discussed. The discourse has a special focus towards better understanding and employing the water-nutrient interactions for improving water productivity at all levels. The complexities of measurement and strategies for improvement of physical or economic water productivity increase as the domain of interest moves from crop-plant to field, farm, system, basin, region and national level. Achieving synchrony between nutrient supply and crop demand without excess or deficiency under various moisture regimes is the key to optimizing trade-offs amongst yield, profit and environmental protection in both large-scale commercial systems in developed countries and small-scale systems in the developing countries. Appropriate water accounting procedures need to be put in place to identify the opportunities for water savings. As pressure on the available land and water increases, higher water productivity is the only solution to providing the food that will be needed with the water that is available.

"It is not the quantity of water applied to a crop, it is the quantity of intelligence applied which determines the result - there is more due to intelligence than water in every case."
Alfred Deakin, 1890.

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Introduction

Improving *water use efficiency* or enhancing *agricultural water productivity* is a critical response to growing water scarcity, including the need to leave enough water in rivers and lakes to sustain ecosystems and to meet the growing demands of cities and industries. Originally, crop physiologists defined water use efficiency as the amount of carbon assimilated and crop yield per unit of transpiration (Viets, 1962) and then later as the amount of biomass or marketable yield per unit of evapotranspiration. Irrigation scientists and engineers have used the term *water (irrigation) use efficiency* to describe how effectively water is delivered to crops and to indicate the amount of water wasted at plot, farm, command, or system level and defined it as "the ratio of irrigation water transpired by the crops of an irrigation farm or project during their growth period to the water diverted from a river or other natural source into the farm or project canal or canals during the same period of time (Israelsen, 1932). This approach was further improved by introducing the concepts of uniformity, adequacy, and sagacity of irrigation (Solomon, 1984; Whittlesey *et al.*, 1986; Solomon and Burt, 1997). Some scholars have even pointed out that the commonly described relationship between water (input, mm or ML) and agricultural product (output, kg or ton) is an *index, and* not efficiency (Skewes, 1997; Barrett Purcell & Associates, 1999). Still this concept of water use efficiency provides only a partial view because it does not indicate the total benefits produced, nor does it specify that water lost by irrigation is often reused by other users (Seckler *et al.*, 2003). The current focus of *water productivity* has evolved to include the benefits and costs of water used for agriculture in terrestrial and aquatic ecosystems. So, *agricultura*l *water productivity* is the ratio of the net benefits from crop, forestry, fishery, livestock and mixed agricultural systems to the amount of water used to produce those benefits (Molden and Oweis, 2007). In its broadest sense, it reflects the objectives of producing more food, income, livelihood and ecological benefits at less social and environmental cost per unit of water consumed. *Physical water productivity* is defined as the ratio of agricultural output to the amount of water consumed, and *economic water productivity* is defined as the value derived per unit of water used, and this has also been used to relate water use in agriculture to nutrition, jobs, welfare and the environment.

Increasing water productivity is particularly appropriate where water is scarce and one needs to realize the full benefits of other production inputs, viz., fertilizers, high- quality seeds, tillage and land formation, and the labor, energy and machinery. Additional reasons to improve agricultural water productivity include (Molden *et al.*, 2010) (i) meeting the rising demands for food and changing diet patterns of a growing, wealthier and increasingly urbanized population, (ii) responding to pressures to reallocate water from agriculture to cities and industries and ensuring water is available for environmental uses and climate change adaptation, and (iii) contributing to poverty reduction and economic growth of poor farmers. Productive use of water means better food and nutrition for families, more income and productive employment. Targeting high water productivity can reduce cost of cultivation of crops and lower energy requirements for water withdrawal. This also reduces the need for additional land and

water resources in irrigated and rain-fed systems. With no gains in water productivity, average annual agricultural evapotranspiration could double in the next 50 years (de Fraiture *et al.*, 2007). Better understanding, measurement and improvement of water productivity thus constitute a strategic response to growing water scarcity, optimization of other production inputs, and enhanced farm incomes and livelihoods.

Measurement of water use efficiency and water productivity

Crop scientists express and measure water use efficiency as the ratio of total biomass or grain yield to water supply or evapotranspiration or transpiration on a daily or seasonal basis (Sinclair *et al.*, 1984). Biomass yield versus evapotranspiration relations have intercepts on the evapotranspiration axis, which are taken to represent direct evaporation from the soil (Hanks, 1974), and yield can be considered a linear function of transpiration, provided water use efficiency does not vary greatly during the season. Linearity of the yield versus evapotranspiration relation denotes that water use efficiency would increase with increase in evapotranspiration as a consequence of increased transpiration/evapotranspiration ratio because the intercept has a constant value. For this reason, water use efficiency also increases with increase in crop water supply up to a certain point (Gajri *et al.*, 1993). Water supply has also been observed to increase fertilizer use efficiency by increasing the availability of applied nutrients, and water and nutrients exhibit interactions in respect of yield and yield components (Prihar *et al.*, 1985; Eck, 1988; Fischer, 1998).

The irrigation system perspective of water use efficiency depends upon the water accounting where losses occur at each stage as water moves from the reservoir (storage losses), conveyed and delivered at the farm gate (conveyance losses), applied to the farm (distribution losses), stored in the soil (application losses) and finally consumed by the crops (crop management losses) for crop production. Depending upon the area of interest, it is possible to measure the water conveyance efficiency, application efficiency, water input efficiency, irrigation water use efficiency and crop water use efficiency (Barrett Purcell & Associates, 1999). Whereas crop water use efficiency compares an output from the system (such as yield or economic return) to crop evapotranspiration the irrigation efficiency often compares an output or amount of water retained in the root zone to an input such as some measure of water applied. The term *'water productivity'* was an attempt to mediate the prevailing complexity and other inherent limitations of the existing concept.

The concept of water productivity (WP) was offered by Kijne *et al.* (2003) as a robust measure of the ability of agricultural systems to convert water into food. So, the basic expression of agricultural water productivity is a measure of output of a given system in relation to the water it consumes, and may be measured for the whole system or parts of it, defined in time and space (Cook *et al.*, 2006).

$$\text{Water productivity} = \frac{\text{Agricultural benefit}}{\text{Water use}}$$

It is normal to represent water productivity in units of kg m^{-3}, where crop production is measured in kg ha^{-1} and water use is estimated as mm of water applied or received as rainfall, converted to m^3 ha^{-1} (1 mm = 10 m^3 ha^{-1}). Alternatively, it may be represented as food (kcal m^{-3}) or its monetary value ($ m^{-3}).

Agricultural systems are defined by plot, field, sub-basin and basin and the crop(s)/cropping patterns followed at each component level. Water productivity values make better sense when the relative comparisons are made at the component parts of the agricultural system. The time period over which water productivity is estimated is determined by the cycle of agricultural production that drives the system. Normally, this would include at least one complete crop cycle (e.g. rice, wheat, maize, vegetables, etc.) extended over a complete year (rice-wheat, maize-wheat, sugarcane, banana, etc.) to account for productive and non-productive water use. Assessment may be extended over several years to derive estimates of average, minimum or maximum water productivity within each season. Cropping systems provide internal benefits in addition to yield, such as fodder, legumes or soil nutrition, which may significantly influence water productivity in subsequent years. Additionally, the patterns of climate, disease and pest infestation, markets, etc. may induce an estimation error at the time of assessment which may, or may not, be representative of the average situation.

Defining the area for estimation

The first step is to define the boundaries of the system for which WP is to be estimated. This is determined by the definition of production system (field, farm, command area, administrative unit) and the area for which water consumption can be defined (plot, field, sub-basin, watershed or basin). Measurement of partial WP for a single crop at field or plot level is the simplest, and some estimation errors may creep in for representation of a large hydrologic system. This shall be explained in a separate section. In rain-fed areas and areas with shallow groundwater levels, WP will vary spatially according to varying water storage capacities of the soil (Bouman *et al,* 2007) and the definition of a particular production system can be underrepresented or overrepresented within areas having a high or low storage capacity.

Estimating the agricultural production: The numerator

Agricultural biomass or production can be expressed in a range of forms, as yield (kg, Mg, t), or food and energy equivalent (kcal), income ($) or other agreed measures of well-being derived from the agricultural system. This may be expressed as:

$$\text{Output per cropped area}\left(\frac{\$}{\text{ha}}\right) = \frac{\text{Production}}{\text{Irrigated cropped area}}$$

$$\text{Output per unit command}\left(\frac{\$}{\text{ha}}\right) = \frac{\text{Production}}{\text{Command area}}$$

Commonly used forms of agricultural production are given in Table 1.

Table 1. Possible forms of agricultural production used for estimating water productivity (adapted from Cook *et al.,* 2007).

Parameter	Agricultural production
Physical water productivity at field, farm or system level	Yield (kg) of biomass, *or* fruit *or* grain
Economic water productivity at farm level	Gross *or* net value of product, *or* net benefits of production (monetary or energy units)
Economic water productivity at basin scale	Any of the above valuations including those derived from livestock, fishery, agroforestry, pastures and plantations.
Macroeconomic water productivity at regional or national scale	Monetary values of all direct and indirect economic benefits minus the associated costs, for all the uses of water in the domain of interest.

Estimation of WP of a principal crop is simple - estimate the yield (kg, t) and agricultural water use (mm, m^3) over an area of interest. For large areas, crop production data may be estimated through random surveys and secondary statistics on crop production.

The economic measure of productivity at field scale is gross margin (GM) for a single product during a single phase of the crop rotation. For areas that contain different production systems and for cross-system comparison a composite measure may be required. The Standardized Gross Value of Production (SGVP) was developed to harmonize the differences in local prices at different locations throughout the world. To obtain SGVP, equivalent yield is calculated based on local prices of the crops grown, compared with the local price of the predominant, locally grown, internationally traded base crop. The second step is to value this equivalent production at world prices. To do this, economists normally use long-term averages of World Bank prices to take care of the distortions caused by year-to-year price fluctuations (Sakthivadivel *et al.*, 1999). For example, if the local price of a commodity (say, pulse crop) is twice the local price of wheat, one may consider the production yield of 2 t ha^{-1} of pulse crop to be equivalent to 4t ha^{-1} of wheat. Total production of all crops is then aggregated on the basis of 'wheat equivalent' and the gross value of output is calculated as this quantity of wheat multiplied by the average world market price of wheat.

$$SGVP = \left[\sum_{crop} A_i Y_i \frac{P_i}{P_b} \right] P_{world}$$

where,
SGVP= Standardized Gross Value of Production
A_i = Area cropped with crop i

Y_i = Yield of crop i
P_i = Local price of crop i
P_b = Local price of base crop
P_{world} = Value of base crop traded at average world market price

However, the full range of economic benefits from agricultural production extends far beyond the simple measure of local production, to include indirect and broader impacts (Hussain *et al.*, 2007) which may include higher employment rates and wages, improved markets for inputs (fertilizers, seeds, machines, chemicals, services) and the outputs (commodities, transport, trade) and a general improvement of the economy and well-being. Multipliers of economy-wide farm/nonfarm multipliers vary widely. Estimates in India suggest a multiplier as low as 1.2 for local schemes and up to about 3 for the country as a whole. Multipliers tend to be larger in developed economies, estimated as high as 6 for Australia (Hill and Tollefeson, 1996). Hussain *et al.* (2007) point out that the most significant measure is of marginal value, which shows the additional value created when water is added or lost when water is not available. The noneconomic benefits of production may be measured through improvements in environmental benefits and services and changes in the Human Development Index (Maxwell, 1999) or the Basic-Needs Index (Davis, 2003).

Estimating the water consumed: The denominator

Water input to a field or an agricultural system is not the same as the water used or depleted for crop production. However, we may work out water use efficiency as output per unit of irrigation supply. Water productivity is estimated from the amount of water directly consumed by the agricultural system (evaporation and transpiration) and not the amount of irrigation water applied or rainfall received (Molden *et al.*, 2003, Molden and Oweis, 2007; Kassam *et al.*, 2007, Molden *et. al.*, 2010). This distinction is increasingly important as we move upscale from field to farm to basin because *water that is taken into the system, but not consumed, is available downstream and hence is excluded from calculation.* At a given scale, this may be estimated through a simple water balance equation or by following the water accounting framework (Molden *et al.*, 2003). At field scale, the key term is evapotranspiration (ET), which may be estimated as:

$$ET = P + I + G \pm Q - \Delta S$$

where, P is precipitation, I is irrigation, G is net groundwater flow, Q is run-on or runoff and ΔS is change in soil water content within the root zone, all measured in millimetres of water. Evapotranspiration of crops is normally estimated from more easily measured climatic variables and the predetermined crop-coefficients (Allen *et al.*, 1998).

Based on the above, two important indicators for 'water applied' and 'water used' will be (Sakthivadivel *et al.*, 1999):

$$\text{Output per unit irrigation supply } \left(\frac{\$}{m^3}\right) = \frac{\text{Production}}{\text{Diverted irrigation supply}}$$

$$\text{Output per unit water consumed } \left(\frac{\$}{m^3}\right) = \frac{\text{Production}}{\text{Volume of water consumed by evapotranspiration}}$$

The relationship between water diversion and depletion is complex, and significant variations exist due to variations in water diverted. The variations average out if one moves out to a larger scale. Interventions should start in areas with the lowest water productivity.

Measuring regional- and basin-level water productivity

At the larger scale of an administrative unit or the sub-basin and basin it is rather impossible to have water balances for each field and the crop. Moreover, at the field or system scales, part of the water delivered is often reused within the field or the system or elsewhere in the basin. To avoid these complications in capturing the reuse and benefits outside the areas of interest, the value of production per unit of crop consumptive water use (CWU) is considered to be a better measure of water productivity (Molden *et al.*, 2003). Consumptive water use in irrigated areas implies the potential evapotranspiration (ET_p), while in rain-fed areas it is the minimum of effective rainfall and ET_p. Depending on the availability of data, resources and competence and the objective of analysis, the estimates of crop yields and the consumptive water use may be made through following either the statistical data on crop yields and historical values of crop coefficients and potential evapotranspiration or the more recent approaches utilizing remote-sensing imagery and crop modelling.

Statistical approach

Long-term (minimum of 3 years) subnational data on detailed land use, crop production, extent of irrigated and rain-fed areas of different crops and the combined total production can help estimate the value of crop production. Climate data (monthly ET_p and rainfall available from IWMI Global Climate and Water Atlas (2001), or FAO and local meteorological departments) and crop coefficients of the major crops can help determine consumptive water use. The method has been described in detail by Amarasinghe *et al.* (2010). The important governing equations are given below:

- Crop water use in irrigated areas (IR) is potential ET during crop growth periods of different seasons and is given by,

$$CWU_{ij}^{IR} = Area_{ij}^{IR} \text{ x } \left(\sum_{k\varepsilon} Kc_{jk} \text{ x } \left\{ \sum_{l\varepsilon months} ET_{ikl}^{p} \right) \right.$$

for the jth crop in the ith season (k denotes the specific crop growth stage, and i denotes the month in the growing season of the crop). Kcs are the crop coefficients over the defined growth periods and ET_ps are monthly reference evapotranspiration values.

- CWU in rain-fed areas is only the effective rainfall during the season, and is estimated as:

$$CWU_{ij}^{RF} = Area_{ij}^{RF} \times \sum_{k \in growth\ periods} \min\left(Kc_{jk}\, ET_{jkl}^{p} \sum_{l \in months} ET_{jkl}^{p}\right)$$

where, ERF_{jkl} is the effective rainfall of lth month in the kth growth period.

- CWU of the area of interest (district, zone, etc.) is estimated as:

$$CWU = \sum_{i \in seasons} \sum_{j \in crops} (CWU_{ij}^{IR} + CWU_{ij}^{RF})$$

- Total WP of the area of interest is estimated by:

$$WP = \frac{\sum_{j \in crops} Average\ yield_j \times (Area_i^{IR} + Area_j^{RF})}{CWU}$$

Integrating use of remote sensing and crop census data

Lack of data required for monitoring the productivity of land and water resources, especially over vast irrigation schemes and river basins can often hamper the application and understanding of the water productivity framework and design of the interventions. Integration of satellite measurements for the climatic data with ancillary *in-situ* data into a geographic information system shall be quite helpful (Bastiaanssen *et al.*, 2003). Remote-sensing measurements are converted to crop yield and to actual evapotranspiration. Existing land use-land cover maps and census data (with ground truthing) are used to map the dominant crops. The yields are calculated from national statistics and interpolated to pixel level using the Normalized Difference Vegetation Index (NDVI) satellite data. Crop evapotranspiration (ET_a) is mapped using a Simplified Surface Energy Balance (SEBAL) model based on the satellite data of land surface temperature and data from the weather stations (Bastiaanssen *et al.*, 2005). WP of dominant crops and total agricultural yield are mapped by dividing crop yield by ET_a for each pixel (Ahmad *et al.*, 2009; Cai and Sharma, 2010). These methods have now been used extensively to map WP of large sub-basins in Pakistan (Ahmad *et al.*, 2009), the Indo-Gangetic basin (Cai *et al.*, 2010), the Karkheh basin in Iran (Ahmad *et al.*, 2009), the Nile basin (Karimi *et. al.*, 2012) and several others.

These WP maps display the spatial variation in great detail (Figure 1). We can identify well-performing 'bright spots' and low-performing 'hot spots' regardless of administrative boundaries. Linking them to rainfall distribution, topography, groundwater level and other spatial information can indicate causal relationships, which is useful to provide information for improved intervention planning (Sharma *et al.*, 2010).

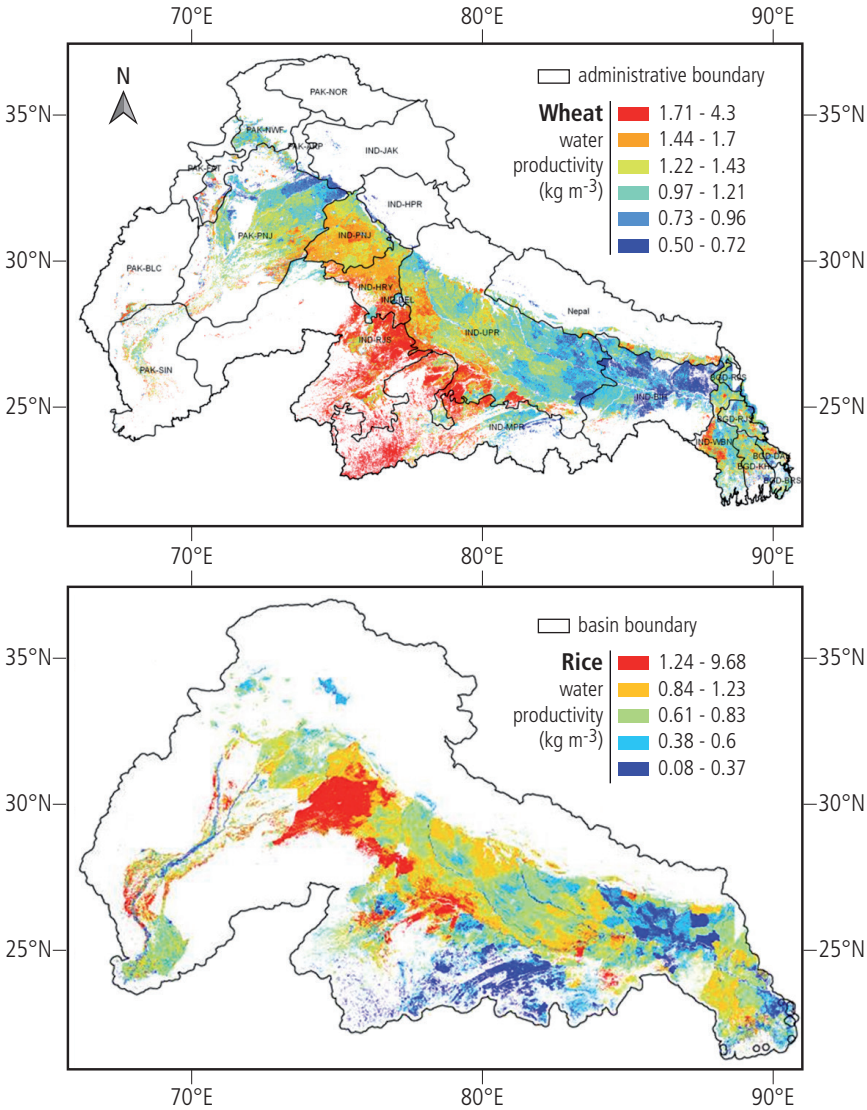

Figure 1. Variations in rice and wheat water productivity in the Indo-Gangetic basin.

Improving agricultural water productivity

Irrigation along with fertilizers and improved seeds has been essential components of a global strategy for increasing agricultural productivity. During the past decades emphasis on improved agricultural water management has been on increasing irrigation water use efficiency, but more recently enhanced emphasis is placed on producing more with relatively less water – increasing water productivity. There is a need to find new ways to increase water productivity by improving biological, economic and environmental output per unit of water used in both irrigated and rain-fed agricultural systems. Physical productivity improvements can be made by obtaining more productive transpiration from rain and irrigation withdrawals, producing more and higher-value crops per unit of transpiration, reducing evaporation, and managing agricultural water deliveries and drainage better. Such opportunities are very diverse and occur at biological, environmental and management levels.

Water productivity at plant level

Actual crop yield and actual evapotranspiration both depend on physiological processes – stomata need to open for carbon inhalation and vapour exhalation. For a given crop variety and climate there is a well-established linear relationship between plant biomass and transpiration (Steduto *et al.*, 2007). Different kinds of plants are more water-efficient in terms of the ratio between biomass and transpiration. C3 crops, such as wheat and barley, are less water-efficient than C4 crops, such as maize and sugarcane. The most water-efficient crops are the CAM (Crassulacean acid metabolism) crops such as cactus and pineapple (xerophytes). One of the most successful strategies of the plant breeders has been to develop varieties with a higher harvest index (ratio of marketable grain yield to total crop biomass), achieving more economic produce per unit of transpiration. This plant-breeding strategy has probably raised the potential for gains in water productivity more than any other agronomic practice over the last 40 years (Keller and Seckler, 2004). The harvest index of wheat and maize improved from about 0.35 before the 1960s to 0.5 in the 1980s (Sayre *et al.*, 1997). This happened during the era of the Green Revolution in Asia and elsewhere. However, it appears that this strategy has achieved its potential and further increase in harvest index has slowed down. New innovations in plant biotechnology like the development of drought-tolerant varieties for arid zones and salt and flood-tolerant rice for the coastal areas are required to make the next breakthrough. Introduction of submergence-tolerant Scuba gene in rice is one such good example (Septiningsih *et. al.,* 2009)

The near linear relationship (in good productive fields) between transpiration and crop production has far-reaching consequences for water needs. Increase in food production in productive areas is achieved with a near proportionate increase in transpired water. Molden *et al.* (2010) identified this as the main reason why increases in food production have caused serious environmental consequences, e.g. steep decline in water tables in the highly productive areas of the Indus basin and elsewhere (Rodell *et al.*, 2009). Feeding more people will require more water to be transpired. An alternative strategy may be to provide higher attention to low productivity areas in Africa and

South Americas where application of small amounts of water and fertilizers can pay much larger dividends (Rockström *et. al.*, 2007, Rockström and Barron, 2007; Sharma *et al.*, 2010).

Water and fertilizer interactions at the field and farm level

Water availability, water use and nutrient supply to plants are closely interacting factors influencing plant growth and yield production. It is generally reported that application of fertilizers enhances water use efficiency by causing greater increase in yield relative to that in evapotranspiration (Viets, 1962; Ritchie, 1983). Evapotranspirational and transpirational water use efficiency can be increased by raising soil nutrient levels. Adequately fertilized soils promote rapid leaf area expansion, thus increasing transpiration, and more rapid ground cover, thus reducing evaporation and increasing evapotranspirational water use efficiency. Raised soil nutrient levels seem to exert additive effects on water use efficiency, and increasing or optimizing yields by adequate application of fertilizers will increase transpiration efficiency of the crop plants (Schmidhalter and Studer, 1998). Plants which have adequately used fertilizers may also show higher drought tolerance (Lahiri, 1980; Wang *et al.*, 2011). Water use efficiency also increases with increase in water supply up to a certain point. Water supply has been observed to increase fertilizer use efficiency by increasing the availability of applied nutrients. In fact, water and nutrients have been shown to exhibit interactions in respect of yield (Prihar *et al.*, 1985; Aggarwal, 2000). Combination effects of nitrogen (N) and irrigation are generally more than the sum of their individual effects. Gajri *et al.* (1993) very conclusively show that in deeply wetted coarse-textured soils with low organic matter, N application and early-post seeding irrigation in wheat enhance profile water use by increasing depth and density of rooting as well as leaf area index and leaf area duration. While better rooting increases capacity of the plant to extract water by increasing the size of the water reservoir, extensive canopy with longer duration increases the plant demand for water. Increased canopy also increases the transpiration component of evapotranspiration. Thus nitrogen application, apart from increasing evapotranspiration and transpiration/evapotranspiration ratios, also increases water use efficiency (Table 2). A strong interaction between N and water for yield, dependence of water use efficiency on nitrogen rate, and nitrogen use efficiency on water supply have important management implications. Similarly, water use efficiency was 119% and 150% higher when only pre-sowing irrigation and pre-sowing irrigation plus phosphorus application were made, respectively, to the wheat crop, as compared to control (Li *et al.*, 2004). Fertilizer rates, over which farmers usually have better control, need to be adjusted properly in relation to the available water supplies.

In several studies, soil nitrogen level was positively related to water use efficiency (Paramweswaran *et al.*, 1981; Heiholdt, 1989). Similarly, applying phosphorus fertilizers increases root density and rooting depth and the amount of water available to plants is increased. Phosphorus, in a balanced soil fertility program, increases water use efficiency and helps crops achieve optimal performance under limited moisture conditions (Payne *et al.*, 1992; Wang *et al.*, 2011). The uptake of water by the plant roots and the transport of the water to other parts of the plant are significantly determined by

Table 2. Nitrogen and irrigation effects on water use efficiency (kg grain ha^{-1} mm^{-1}) and N-use efficiency (kg grain (kg fertilizer N)$^{-1}$) in wheat at Ludhiana, India (adapted from Gajri *et al.*, 1993).

Irrigation (mm)	Water use efficiency N rate (kg ha^{-1})				N-use efficiency N rate (kg ha^{-1})		
	0	40	80	120	40	80	120
No irrigation (rain-fed)	2.8	4.4	6.3	3.6	5.3	4.8	0.9
50	5.2	9.4	10.3	10.9	23.3	12.0	9.8
120	5.7	8.4	10.3	9.0	23.0	17.6	8.8
300	5.1	7.0	8.6	8.8	19.5	20.0	14.8

potassium. Potash fertilizers are directly involved in the water management of the plant since it reduces water loss through transpiration. In sandy soils, water use efficiency for total dry matter production is increased by potassium application (Schmidhalter and Studer, 1998; Prasad *et al.*, 2000). Based on the results of a number of on-farm trials in the savannahs prone to water scarcity, Rockstrom and Baron (2007) also concluded that crop transpiration and yield relationship show non-linearity under on-farm and low-yield conditions. With integrated soil and water management, focusing on mitigation of dry spells and improved soil fertility can potentially more than double on-farm yields. In most cases, increasing or optimizing yields by the use of adequate fertilizers will increase water use efficiency.

Typically, in situations where yield is less than 40-50% of the potential, non-water factors such as soil fertility, limit yield and crop water productivity. However, when yield levels are above 40-50% of their potential, yield gains come at a near proportionate increase in the amount of evapotranspiration (Figure 2); thus incremental gains in water productivity become smaller as yields become higher. For example, the application of relatively small amounts of water and fertilizers for raising yields from 1 to 2 t ha^{-1} will lead to much higher gains in water productivity than doubling the yields from 4 to 8 t ha^{-1} (Molden *et al.*, 2010).

Thus, there appears to be a considerable scope for improving the productivity relative to evapotranspiration before reaching the upper limit. This variability is due to management practices and is important because it offers hope for possible improvements in the ratio between evapotranspiration and marketable yield. For the high productivity fields, balanced use of fertilizers should be encouraged to ensure sustainable productivity in the intensive cropping system as its lack could lead to significant decline in yields and water use efficiency with lapse of time. Additions of organic materials to soil increases soil water-holding capacity, which in turn improves water availability to plants (Fan *et al.*, 2005).

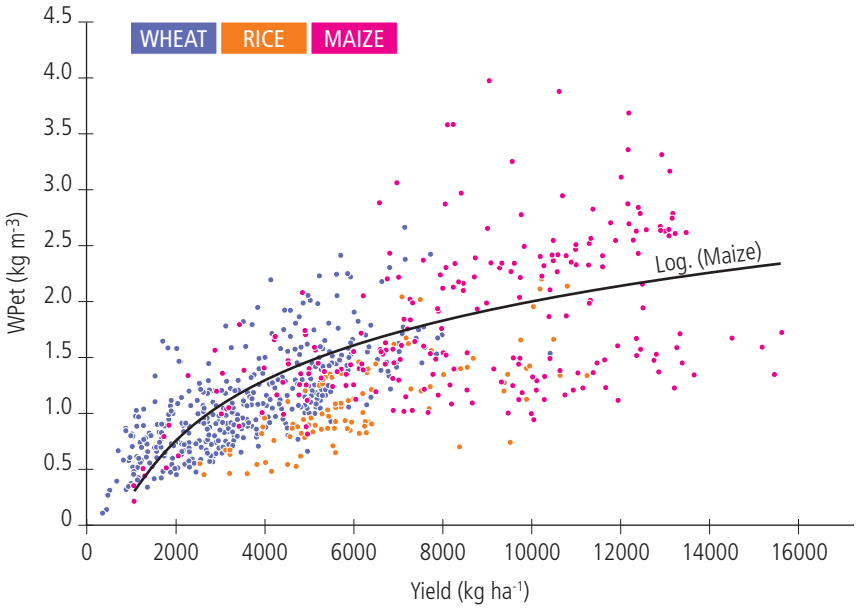

Figure 2. Water productivity gains are higher at lower yield levels and tend to be proportionate at higher yield levels (adapted from Zwart and Bastiaanssen, 2004).

Water productivity under scarce water conditions

Serious water deficits and deteriorating environmental quality are threatening agricultural sustainability in large parts of Asia and Africa. To increase crop yield per unit of water requires both better cultivars and better agronomy. The challenge is to manage the crop or improve its genetic makeup. After analysing a large dataset Passioura (2006) found that in the field, the upper limit of water productivity of well-managed water-limited cereal crops is typically 20 kg ha^{-1} mm^{-1}. If the productivity is markedly less than this (e.g. rain-fed water use efficiency in China is 2.3 kg ha^{-1} mm^{-1}, far less than the potential; Deng *et al.*, 2006), it is likely that major stresses other than water appear, such as poor nutrition and diseases. Unfortunately, there are no genetic transformations that are likely to improve water productivity greatly. Small and timely irrigation, along with management of soil nutrients is the focal issue which is shown to increase water use efficiency by 10-25%. Often, soil fertility is the limiting factor to increased yields in rain-fed agriculture. Soil degradation, through nutrient depletion and loss of organic matter, causes serious yield decline closely related to water determinants, as it affects water availability for crops, due to poor rainfall infiltration, and plant water uptake, due to weak roots. Studies have even shown that within certain limits, nitrogen and water supply have substituted for each other in increasing crop yields (Gajri *et al.*, 1993). In sub-Saharan Africa, soil nutrient mining is particularly severe. By farming intensively without replenishing soil nutrients, farmers across sub-

Saharan Africa have lost nitrogen, phosphorus, and potassium on an average of 22, 2.5 and 15 kg ha^{-1}, respectively, annually over the past 30 years – the yearly equivalent of US$ 4 billion worth of fertilizers. As a result, yields are meagre (IFDC, 2006; Gilbert, 2012). Similarly, in India, participatory watershed management trials in more than 300 villages showed that farming practices had depleted soils not only in macronutrients but also in micronutrients such as zinc and boron, and secondary nutrients such as sulphur beyond the critical limits. A substantial increase in crop yields of 70-120% was achieved when both micronutrients and adequate nitrogen and phosphorus were applied to a number of rain-fed crops (maize, sorghum, beans, pigeon pea, and groundnut) in farmers' fields (Rego *et al.*, 2005). Therefore, investment in soil fertility directly improved water management. The rainwater productivity was increased by 70-100% for maize, groundnut, mung bean, castor and sorghum by adding boron, zinc and sulphur. Even in terms of economic returns, rainwater productivity was substantially higher by 1.50 to 1.75 times (Rego *et al.*, 2005).

The low water use efficiency in farmer's fields compared with well-managed experimental sites indicates that more efforts are needed to transfer water saving technologies to the farmers. Under such scenarios, water-saving agriculture and water-saving irrigation technologies, including deficit irrigation, low pressure irrigation, subsurface drips, drip irrigation under plastic covers, furrow irrigation, rainfall harvesting and conservation agriculture shall be quite helpful. Water-saving agriculture includes farming practices that are able to take full advantage of the natural rainfall and irrigation facilities. Where water is more limiting than land, it is better to maximize yield per unit of water and not yield per unit of land. Limited or deficit irrigation is becoming an accepted strategy in West Asia and North Africa (Table 3; Oweis and Hachum, 2009) and northern China regions. Supplemental irrigation, the combination of dryland farming and limited irrigation, is an ideal choice for improving crop yields in rain-fed regions (Deng *et al.*, 2006). Results from a nationwide study in India showed that water used in supplemental irrigation had the highest marginal productivity and with improved management, an average increase of 50% in total production can be achieved with a single supplemental irrigation. Water harvesting and supplemental irrigation are economically viable even at the national level. Droughts have very mild impacts on productivity when farmers are equipped with supplemental irrigation (Sharma *et*

Table 3. Gains in water productivity for wheat grain under rain-fed and supplemental irrigation with different levels of nitrogen in northern Syria (source: Oweis and Hachum, 2009).

Nitrogen application rate (kg N ha^{-1})	Water productivity (kg grain m^{-3})	
	Rain-fed water	Irrigation water (one supplemental irrigation)
0	0.54	0.81
50	0.89	1.41
100	0.84	2.14
150	0.81	1.40

al., 2010). Increasing the availability of plant nutrients increases yields as well as water use by the crop; however, the increase in water use is usually small – generally < 25% (Power, 1983). A classic example is provided by Carlson *et al.* (1959) who showed that maize yields were doubled primarily by N fertilizers whereas transpiration varied by less than 10%.

On-farm water use efficiency can be further improved by moving to a more efficient irrigation system. Maximum values of water use efficiency and harvest index occur under appropriately controlled water conditions. Micro irrigation has developed rapidly in recent years and adopted for a variety of high-value crops in water-scarce regions. In northwest China, traditional furrow or border (flood) irrigation methods have an annual average water demand of about 7,320 m^3 ha^{-1} in contrast to only 3,250 m^3 ha^{-1} for fields under micro irrigation (Deng *et al.*, 2006). Use of subsurface drip irrigation has also progressed from being a novelty employed by researchers to an accepted method of irrigation of both annual and perennial crops. Analyses of the data for 15 years at Water Management Research Laboratory have demonstrated a significant yield and water use efficiency increase in a number of crops (tomato, cotton, alfalfa, and cantaloupe). The use of high-frequency irrigation resulted in reduced deep percolation and increased use of water from shallow groundwater when crops were grown in high water table areas (Ayars *et al.*, 1999). In the Middle East, wheat yields were twice as high under subsoil irrigation compared with furrow irrigation. Water use efficiency ranged from 1.64 to 3.34 in subsoil irrigation and from 0.46 to 1.2 kg grain m^{-3} in furrow irrigation; and N release from soil was also much higher under subsoil irrigation (11-216 kg N ha^{-1}) than under furrow irrigation (11 to 33 kg N ha^{-1}) (Banedjschafle *et al.*, 2008). Without adequate water, nitrogen use efficiency remains low, resulting in substantial nitrogen losses. Too much water leads to excessive NO_3–N leaching and lower water productivity. The lack of N is a cause of low water productivity but too much of it leads to lower nitrogen use efficiency and higher losses. Though increased NO_3–N leaching is an inevitable by-product of increased WP, its adverse impacts can greatly be reduced by managing the quantity and timing of nitrogen fertilizer and water application (Nangia *et al.*, 2008). Better inorganic nitrogen and water management lead to higher water productivity and, at the same time, less NO_3–N leaching. The use of slow- or controlled-release fertilizers can further mitigate the NO_3–N leaching.

Water productivity under paddy fields

A unique feature of most commonly cultivated irrigated lowland rice culture is crop growth in submerged soil. In transplanted rice, fields are puddled to reduce percolation and are flooded before planting and the daily losses are made up through frequent irrigations. Rice can also be planted by direct seeding, using either wet seeding, with pre-germinated seed broadcast on a puddled soil surface or dry seeding after normal soil tillage with flooding after the seedlings are established. Bhuyian *et al.* (1995) showed that wet-seeded rice culture requiring less water is superior to the traditional transplanted rice in terms of water use efficiency. More recently, aerobic rice, system of rice intensification (SRI) technique and irrigating rice fields with drips and micro sprinklers are also gaining ground. For a typical 100-day season of modern high-

yielding rice, the total water input varies from 700 to 5,300 mm, depending on soil, climate and hydrologic conditions, with 1,000-2,000 mm as a typical value for many lowland areas (Tuong and Bouman, 2003). Water productivity of lowland rice (based on irrigation+rainfall) varies from 0.2 to 1.2 kg m^{-3} and is much less than for wheat (0.8 to 1.6 kg m^{-3}) and maize (1.6 to 3.9 kg m^{-3}). Water productivity of rice may be improved through reducing large amounts of unproductive water outflows during the crop growth and using the rain more efficiently. Instead of keeping the rice field continuously flooded with 5-10 cm of water, the floodwater depth can be decreased, the soil can be kept around saturation or alternate wetting and drying regimes can be imposed. Dry-seeded rice technology offers a significant opportunity for conserving irrigation water by using rainfall more effectively. Studies have shown that maintaining a field bund of 22 cm height around rice fields had helped in capturing more than 95% of seasonal rainfall in paddy fields and thus reduced the need for irrigation (Humphreys *et al.*, 2005). Dry-seeded rice significantly increased water productivity in respect of irrigation over wet-seeded and transplanted rice. Aerobic rice, a new approach to reducing water inputs in rice, is to grow the crop like an irrigated upland crop, such as wheat and maize. With suitable stress-tolerant cultivars, the potential water savings of aerobic rice are large, especially on soils with high percolation rates. On a regional basis, large amounts of irrigation water may be saved by delaying the rice transplanting to avoid the excessively hot summer season. To bring some semblance to the fast-depleting water tables (assigned to large-scale summer paddy cultivation) in Indian Punjab, the government enacted a legislation to force all farmers to delay (from as early as 10th May) transplanting of paddy to 15th of June. Studies have shown that this legislation resulted in real water savings of about 2.18 billion m^3 (7% of annual draft in the state) of water (Sharma and Ambili, 2010).

Studies have also shown that water productivity in rice was significantly increased by N application which increased grain yield through an increased biomass and grain number. In irrigation systems with a shallow water table, optimal N management is as important as water saving irrigation to enhance water productivity. Fischer (1998) estimated that if the technologies that affect nutrient utilization by the rice crop remain unchanged, the production increase will require almost 300% more than the present application rate of N alone in irrigated environments. Achieving synchrony between N supply and crop demand without excess or deficiency under various moisture regimes is the key to optimizing trade-offs amongst yield, profit, and environmental protection in both large-scale systems in developed countries and small-scale systems in developing countries. N fertilizer losses in water-intensive paddy fields are thus a symptom of incongruity between N supply and crop demand rather than a driving force of N efficiency and thus provide significant opportunities by improved management of nitrogen and water resources.

Water productivity of large systems/river basins

At larger regional or river-basin scales with more users, and more interaction between users, water productivity issues become increasingly complex. Minimizing non-productive depletion of water flows, improving management of existing irrigation

facilities and reallocating and co-managing water among uses by allocating water to high-value uses and the outflows for the environment and downstream, are some of the pathways for improving water productivity at the basin level. The primary options to create 'new water' are to transfer the consumptive portion of existing agricultural allocations to other uses, construction of desalination facilities and the creation of additional storage (at the surface or in the aquifers) of surplus floodwaters (Frederiksen and Allen, 2011). At the same time, the common water conservation practices – including urban indoor and outdoor efficiency programs, precision irrigation systems, improvement in soil moisture monitoring and management, deficit irrigation and other approaches – have enormous potential to conserve water in several basins. We must have appropriate water-accounting procedures in place in order to identify the opportunities for water savings. Each basin is different, and therefore the mix of demand- and supply-side solutions will vary according to what is hydrologically, economically, socially and politically possible (Gleick *et al.*, 2011).

A recent assessment of water productivity in ten major river basins across Asia, Africa and South America, representing a range of agro-climatic and socioeconomic conditions showed that there was very high inter-basin and intra-basin variability, attributed mainly to the lack of inputs (including fertilizers), and poor water and crop management (Cai *et al.*, 2011). Intensive farming in the Asian basins (Yellow River, Indus-Ganges, Mekong, and Karkheh) produces much greater agricultural outputs and higher water productivity. Largely subsistence agriculture in African basins (Limpopo,

Table 4. Water productivity of important crops in some major river basins in Asia and Africa (adapted from Cai *et. al.*, 2011).

Basin	Water source	Cropland area (Mha)	Crop types	Yields (t ha^{-1})	Water productivity (kg m^{-3})
Yellow River	irrigated	7.5	wheat	3.7	1.39
			maize	5.3	0.97
			rice	5.4	0.5
Mekong	rain-fed	8.80	maize	3.0	1.09
			soybean	1.40	0.41
	irrigated	3.28	rice	2.87	0.43
			sugarcane	64.5	9.81
			maize	3.79	0.58
Indo-Gangetic	irrigated	62.1	rice	2.6	0.74
			wheat	2.65	0.94
Limpopo	rain-fed	2.06	maize	3.6	0.14
Volta	irrigated	0.036	millet	1.0	0.1
Sao Francisco	irrigated	0.355	maize	1.3	0.15
			sorghum	1.0	0.1
			millet	0.9	0.08

Niger, and Volta) has significantly lower water productivity (Table 4).Yields of the major crops (maize, wheat, rice) vary both across and within basins. All three crops in the Yellow River basin have relatively high yields. The Indus-Ganges basins have the most intensive cultivation, but have relatively low yields overall for both rice and wheat, which are the major sources of food and income.

There is large intra-basin variability in all the basins. The average yield of maize in the Limpopo is 3.6 t ha^{-1}. While the irrigated commercial farms with good inputs of fertilizers and crop management yield as high as 9 t ha^{-1}, the large areas of subsistence farms, which are threatened by frequent droughts and soil nutrient depletion, yield less than 2 t ha^{-1}. The Indian states of Punjab and Haryana, the "bright spots" in the Indus-Ganges basin yield more than double elsewhere (Figure 1). Similarly, variation in water productivity in different basins may be related to the use of fertilizers, crop management and other inputs. Water productivity of maize is highest in the Yellow River (0.97 kg m^{-3} , fertilizer use of > 250 kg ha^{-1}), followed by Mekong (0.58 kg m^{-3}, fertilizer use ~ 120 kg ha^{-1}) and lowest in Limpopo (0.14 kg m^{-3}, fertilizer use < 30 kg ha^{-1}). Higher spatial variation in water productivity suggests greater chances to close the gap between the good and poor performers. Understanding the reasons for these differences at the regional or water-basin scale would both assess the potential for improvement and identify priority interventions in low-performing areas.

Causes of variation of water productivity

At the large scale of a country or river basin, besides the biophysical aspects, the level of socioeconomic development has a significant impact on agriculture. In most cases, the higher the contribution of agriculture to the gross domestic product, the higher the incidence of poverty (Hanjra and Gichuki, 2008). In turn, this limits farmers' capacity to increase inputs to agriculture, improve water productivity, and cope with droughts and floods. The African basins mostly rely on rain-fed agriculture with poor infrastructure, low inputs of fertilizers and irrigation, and consequently low crop yields and low crop water productivity. Water stress is a determining factor for all regions. Water for crop production is a concern in most areas including the extremely water-scarce basins. Water scarcity has worsened over the years and the trend will continue due to competitive demand from other sectors. Lack of appropriate diversion and storage structures exposes farmlands to droughts and sometimes even to floods.

Improved seed varieties, fertilizers, pesticides, and energy for tillage and other operations are critical inputs for large areas of low productivity. Land degradation is often another serious problem. Combined management of soil, water, plants and pests is required to overcome these constraints and secure improvements in yield (Bossio *et al.,* 2008) and water productivity. Additional threats are emerging in the form of environmental degradation and climate change. As agriculture intensifies it almost certainly has negative impacts on the environment (Bakkes *et al.*, 2009). In closed basins, where there is competitive demand for water, the need for environmental flows from the rivers is often ignored. The Yellow River ceased to reach the sea in the 1990s.The Indus is another closed basin where both surface water and groundwater are overexploited, causing significant declines in groundwater table, which threatens

sustainability of intensive agricultural systems (Sharma *et al.*, 2010). For the limited quantity of water left in rivers and aquifers, water quality often becomes a major concern. A survey in the Yellow River in 2007 found that about 34% of the river system registered a level lower than level V (Level Five) for water quality, which is considered unfit for any economic activity including agriculture. In the lower parts of the Ganges basin, arsenic contamination of groundwater is a threatening menace and is linked to overexploitation of groundwater (Chakraborty, 2004). Nonpoint source pollution from agriculture is a major threat to water quality in areas of intensive irrigation, where it is often accompanied by high fertilizer inputs (FAO, 1996). The severely degraded water quality threatens water supplies, and consequently, the water productivity. Similarly, climate-change-induced extreme climatic events, such as shorter and more intense rainy seasons and longer and more intense dry seasons will make agriculture, especially rain-fed agriculture, more vulnerable and thus lower the agricultural water productivity. However, further precise assessments of the impact of climate change on crop water productivity are especially needed.

Improving regional- or basin-level water productivity

Large gains in water productivity can be achieved by growing suitable crops in places where climate and management practices enable high water productivity and selling them to places with lower water productivity. Good analysis of basin-level water productivity maps helps compare the "bright spots" and "hot spots" to identify the visible yield gaps. Crop water productivity values with remote sensing at the pixel level provides explicit descriptions of both the magnitude and the variation (Figure 2) (Cai *et al.*, 2010, Zwart and Bastiaanssen, 2004). The next step is to make an assessment of the biophysical potential through local analysis based on solar radiation and soil of the region; to explore water-fertilizer applications in conjunction with crop-genetic innovations. This approach remains the major strategy to achieve the world's long-term goal of higher productivity and food security (Cai *et al.*, 2011). Improving WP through better water management is central to the solutions for improved productivity. Reliable, low-cost irrigation along with the critical inputs would enable poor farmers to improve their productivity.

Conclusions

During the last 50 years, the original concept of 'water-use efficiency' has been considerably enhanced to include 'crop productivity or value per drop of water'. In its broadest sense it relates to the net socio-economic and environmental benefits achieved through the use of water in agriculture. The more commonly used concept of 'water productivity' and its measurement at various scales is a robust measure of the ability of agricultural systems to convert water into food. Increasing water productivity is particularly important where water is scarce compared with other resources involved in production. While water productivity increases with increase in water supply up to

a certain point, water supply also improves fertilizer-use efficiency by increasing the availability of applied nutrients.

The complexities of measurements of physical or economic water productivity increase as the domain of interest moves from crop-plant to field, farm, system, basin, region and national level. An important fact to appreciate is that the water input to a field or an agricultural system is not the same as the water used or depleted for crop production as the water that is taken into the system, but not consumed, is available downstream and hence excluded from the estimation. Besides the conventional methods, the use of remote-sensing satellite data and crop modelling has helped comprehensively map the variations in basin- or regional-level water productivity and identify the potential areas for appropriate interventions.

Development of crop varieties with a higher harvest index during the Green Revolution era was the most successful strategy to improve land and water productivity, but further increases have slowed down. Additional increase in crop production is now achieved with near proportionate increase in water consumption leading to over-exploitation of water resources in the productive areas. Alternatively, dry-spell mitigation and soil-fertility management can potentially more than double the on-farm yields in the vast low-productivity rain-fed areas. Fertilizer-mediated better rooting increases the capacity of the plant to extract water by increasing the size of the water reservoir and extensive canopy with longer-duration increases in plant demand for water. Fertilizer rates (including secondary and micronutrients), over which farmers have better control, need to be adjusted properly in relation to available water supplies. Very low water productivity levels, even under water-scarcity conditions, might indicate that major stresses other than water are at work, such as poor nutrition and diseases. In large rain-fed areas of sub-Saharan Africa, often soil fertility is the limiting factor to increased yields. Achieving synchrony between nutrient supply and crop demand without excess or deficiency under various moisture regimes (including lowland paddy) is the key to optimizing trade-offs amongst yield, profit and environmental protection in both large-scale systems in developed countries and small-scale systems in the developing countries.

At large river-basin scales with diverse and interacting uses and users, the water productivity issues become increasingly complex. Options for improving water productivity include reallocation and co-management of the resources among the high-value uses while maintaining a healthy ecosystem. Appropriate water accounting procedures need to be put in place to identify the opportunities for water savings. Large gains in water productivity can be achieved by growing suitable crops in places where climate and management practices enable high water productivity and selling them to places with lower water productivity. Presently, there is great scope for increasing economic water productivity by increasing the value generated by water use and decreasing the associated costs. However, a number of key drivers including climate change, urbanization, changes in diets and populations, and change in prices of commodities (outputs) and inputs (seeds, fertilizers, energy, etc.) will require that systems need to rapidly respond to take advantage of potential gains in water productivity.

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