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# Improvement of Water Use Efficiency in Irrigated Agriculture: A Review

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**Abstract:** Water scarcity and the increasing global demand for water in many sectors, including agriculture, has became a global concern. The rapid growing world population and the adverse impacts of climate change led to growing competition for water use by industrial and urban users for agriculture to secure enough food. Irrigated agriculture is an important role in total agriculture and provides humanity with a wide range of agricultural products, including fruits, vegetables, grains and cereals. Effective management for water use is the only way to save water for the increasing irrigated agriculture. Different approaches have been adopted to reduce the damage caused by drought; among these approaches is water productivity or water use efficiency WUE. A crop with high WUE should have greater yield than a crop with low WUE.

**Key words:** Water use efficiency, drought, irrigated agriculture, plant improvement

## INTRODUCTION

More than 40% of global land is under arid or semi-arid climatic conditions (Gamo, 1999). In the arid and semi-arid environments water is the most limiting factor in reducing agricultural production (Cattivelli *et al*., 2008). Drought is a complex process that needs to be understood by many disciplines in order to overcome and minimize the damage that it causes. The responses of plant to drought is also complex because conditions vary in the frequency of dry and wet periods, the degree and timing of drought and the patterns of soil and atmospheric water deficits (Deng *et al*., 2006; Boutraa, 2010a, b). Drought is a kind of water stress that is related to other stresses, such as high temperature stress, salt stress, cold stress and so on (Niu *et al*., 1996; Shao *et al*., 2005) and that what made drought more complicated. Currently, drought research has been one of the main priorities in plant breeding programs worldwide. Over the past forty years many crop breeders and plant physiologists have made great efforts to improve the drought tolerance of a range of agricultural and horticultural crops. Shortage of water at different scales lead to drought with all its agricultural impacts (Morison *et al*., 2008) and the climate change has made the situation worse by reducing the amount of rainfall and therefore the amount of water available for agriculture (IPCC, 2007). Shortage of water has forced the decision makers and particularly in countries with less water, to reduce the water use in agriculture. As a result farmers are face with legislative restrictions on use of water (Morison *et al*., 2008).

For better use of water in agriculture in water-limited environments, efforts are needed from different research disciplines; plant breeders, plant physiologists, agronomists, plant biotechnologists, water engineers and experts, to develop new approaches in water use. For example, is it possible to find or develop crops that require less water and maintain high yield productivity? Many scientists are sceptical of the role of genetic engineering and biotechnology in improving water use efficiency. Because the manipulation of single of few genes is unlikely to significantly contribute in the improvement of such complex trait (Passioura, 2004; Parry *et al*., 2005). One of the main adopted approach to breeding for drought tolerance to overcome the impacts of water shortage on agricultural production is to concentrate on increasing what has come to be known as water productivity or water use efficiency WUE of the crop (Jones, 1993), which is defined as productivity term-output of crop per unit of water (Jones, 2004).

The objectives of the present study are to review (1) the irrigated agriculture and its ability to meet the growing population food needs, (2) the concepts of water use efficiency and (3) the ways to improve WUE from agronomic point of view.

## ROLE OF IRRIGATED AGRICULTURE

Irrigated agriculture is an important component of total agriculture worldwide and covers a wide range of agricultural products such as vegetables, fruits, cereals (Howell, 2001). Figure 1 shows the 2025 baseline simulation a global map of irrigated agriculture area as a share of total cultivated area by country. Most agriculture in the Middle East countries relies on irrigation; for example irrigated agriculture is Iraq, Saudi Arabia and Iran

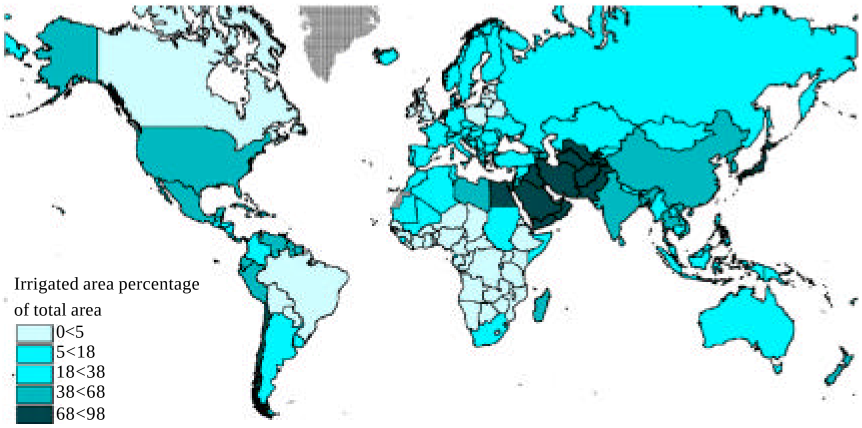


Fig. 1: Irrigated harvested area as a share of total crop harvested area, 2025 baseline simulation (Rosegrant *et al*., 2002)

Table 1: Global water balance and irrigation water withdrawal in 1997/99 and 2030

| Factors | Unit | Sub-Saharan Africa | Latin America | Near East/North Africa | South Asia | East Asia | All developing countries |
|---|---|---|---|---|---|---|---|
| Precipitation | mm | 880 | 1534 | 181 | 1093 | 1252 | 1043 |
| **Water balance** | | | | | | | |
| Renewable water resources | km$^3$ | 3450 | 13409 | 541 | 2469 | 8609 | 28477 |
| **Irrigation water withdrawal** | | | | | | | |
| Irrigation efficiency 1997/99 | % | 33 | 25 | 40 | 44 | 33 | 38 |
| Irrigation water withdrawal 1997/99 | km3 | 80 | 182 | 287 | 895 | 684 | 2128 |
| idem as percent of RWR | % | 2 | 1 | 53 | 36 | 8 | 7 |
| Irrigation efficiency 2030 | % | 37 | 25 | 53 | 49 | 34 | 42 |
| Irrigation water withdrawal 2030 | km3 | 115 | 241 | 315 | 1021 | 728 | 2420 |
| Idem as percent of RWR | % | 3 | 2 | 58 | 41 | 8 | 8 |

Faures *et al*. (2002)

is expected to account for 92, 84 and 73%, respectively. It is expected that in the USA and Asia, 67 and 50%, of agriculture will be under irrigation by the year 2025, respectively. In contrast, to the Middle East, USA and Asia, irrigated agriculture in Sub-Saharan Africa is expected to use less than 5% of crop land (Calzadilla *et al*., 2010). It is also expected that the developing countries as a whole, are to increase their irrigated land from 202 millions hectares in 1997-99 to 242 millions hectares by 2030 (FAO, 2002).

As rainfed agriculture, irrigated agriculture greatly contributes in food production, for example, it provides 40% of the global cereal production (De Fraiture and Wichelns, 2010) and it is expected that the contribution of irrigated agriculture will increase in the coming decades (Bruinsma, 2003). Agriculture is the largest consumer of water, as around 70% of all freshwater withdrawals are used for food production (Calzadilla *et al*., 2010). The irrigated areas represents approximately 18% of the total cropped land in 2003 (FAOSTAT, 2006), resulting in the production of 40-45% of the food worldwide (Doll and Siebert, 2002). Irrigation has long been considered to be a wasteful, because of the unnecessary high amount of water use (Bhatia and Falkenmark, 1992). The objective of irrigation is to meet the evapo-transpiration requirements of a crop, by apply sufficient amount of water in the soil, taking in consideration the local climate, the density of plant cover and the growth stage of the crop (Perry *et al*., 2009). In arid and semi arid environments, regions with less rainfall, there is an increase competition for water between agriculture and other water users (De Fraiture and Wichelns, 2010). Agricultural water use has grown in recent decades due to the increase in global population and the change in the type of food that require more water than traditional foods (Molden, 2007) (Table 1). Many workers in the water field research called of urgent action to be taken to avoid global problems (Alcamo *et al*., 1997; Shiklomanov, 2000; Falkenmark and Rockstrom, 2004; De Fraiture and Wichelns, 2010). A range of strategies need to be implemented globally to reduce the impacts of water scarcity in agriculture. These could be implemented in collaboration between through research organisations and decision makers. The outcome of this research is the better use of water in irrigated agriculture (Molden, 2007).

## IMPACTS OF CLIMATE CHANGE ON IRRIGATION REQUIREMENTS

To estimate how long term irrigation requirements average might change due to the expected climate change

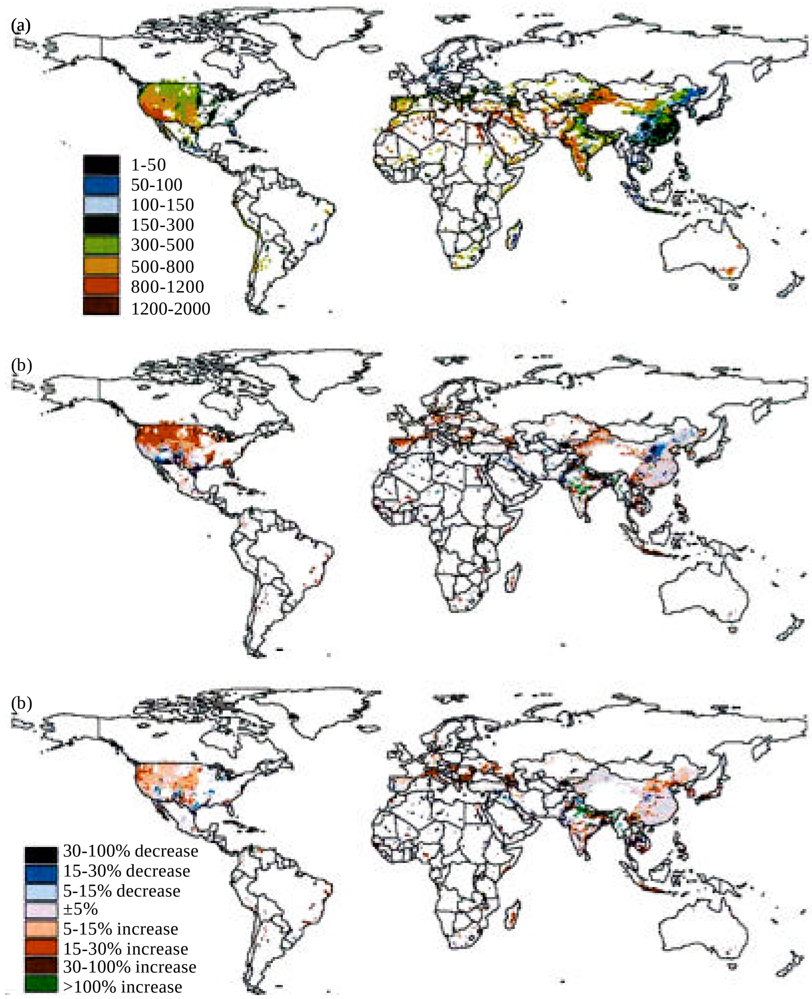


Fig. 2: (a) Net irrigation requirement (IRnet) per unit irrigated area under baseline climate (1961-1990) (mm $year^{-1}$). (b) Change of IRnet between baseline climatic condition and the 2020s, due to climate change. (c) Same as (b), but due to climate change (Doll, 2002)

conditions of the 2020s, a global model of irrigation requirements, GIM (Global irrigation Model) has been implemented (Doll and Siebert, 2002) (Fig. 2). The climatic input of the GIM is based on long term observation of monthly values of precipitation, temperature, sunshine hours and number of wet days. Gross irrigation requirement is the total amount of water that must be used by irrigation to achieve optimal crop productivity (Doll, 2002).

## WATER USE EFFICIENCY WUE

Water Use Efficiency (WUE) or water productivity has emerged from the ideas of drought resistance and drought tolerance (Passioura, 2006). At the beginning of the sixties of the last Century, water use efficiency has been generally defined in agronomy (Viets, 1962) as:

$$WUE = \frac{\text{Crop yield (usually the economic yield)}}{\text{Water used to produce the yield}} \quad (1)$$

The term Water Use Efficiency can be used at wide range of scales; for example, it can be used at the farm, the field, the plant, or down to plant parts level, such as the leaf (Morison *et al*., 2008). In agriculture, WUE can be used at different levels; at leaf level (leaf photosynthesis rate per transpiration rate), at whole plant level (the ratio of total dry mass to water use) and at the final economic yield (crop grain per unit area to transpiration) (Hong-Xing *et al*., 2007; Ali and Talukder, 2008). Water productivity or water use efficiency has different meanings to different people (Passioura, 2006; Kijne *et al*., 2003; Pereira *et al*., 2002; Ali and Talukder, 2008; Zoebl, 2006). For example, to irrigation engineer can mean the amount of water used to produce a crop (Ali and Talukder, 2008). WUE has been described as the crop yield per unit of water used (Sinclair *et al*., 1984). The different proposed definitions of WUE are difficult to apply because a number of management factors can affect yield between irrigated and dryland agriculture. These factors include fertility, crop variety, pest management, sowing date, soil water content, planting density and rows pacing (Howell, 2001). In crop production, the aim of improving WUE, is to produce more economic yield with less water when water is a limiting factor (Boutraa and Sanders, 2001a; Boutraa, 2010a), such as in arid and semi arid regions across the globe. In crop production, WUE can be expressed by different indicators resulting in different options (Ali and Talukder, 2008):

$$WUE_1 = \frac{\text{Grain or seed yield}}{\text{Water applied to the field}} (\text{kg ha}^{-1}\ \text{cm}^{-1}) \quad (2)$$

$$WUE_2 = \frac{\text{Total dry matter yield}}{\text{Water applied to the field}} (\text{kg ha}^{-1}\ \text{cm}^{-1}) \quad (3)$$

$$WUE_3 = \frac{\text{Total monetary value}}{\text{Water applied to the field}} (\$\ \text{m}^{-3}) \quad (4)$$

Equations 2 and 3 are appropriate in a single crop, while Eq. 4 is more appropriate for multiple cultures or under limiting water conditions without limiting land (Ali, 2006). There is a substantial scope to improve water use efficiency in both rainfed and irrigated agriculture; particularly in Sub Saharan Africa and South Asia where crop production is reduced because of poor soil nutrient and low water supply (Rockstrom *et al*., 2003; Nangia *et al*., 2008).

## SAVING WATER FOR IRRIGATED AGRICULTURE

Water saving agriculture, is a notion to describe the combination of agronomic, physiological, biotechnological/genetic and engineering approaches to reduce agricultural water use (Morison *et al*., 2008). Many workers focused on reducing the use of irrigation in hot, dry environment, as in these environments agricultural products require high water use due to the high rate of evapo-transpiration (Wallace, 2000; Gregory, 2004). Improving water use efficiency implies how effectively we can increase the outcome of the crop with the current available water (Passioura, 2006; Ali and Talukder, 2008). At the global level, the major grain exporters (USA, Canada, France, Australia and Argentina) produce grains in highly productive rainfed lands and the major grain importers rely on irrigation to produce grains (De Fraiture and Wichelns, 2010). The main strategy that needs to be implemented in improving water productivity in rainfed agriculture is the wise management of crops and water resources in addition to the improvement of the genetic makeup of crops to maximise the capture of water in plant biomass production (Passioura, 2006). Whereas, in irrigated land, there is a need to better manage and use water efficiently, not only because of water shortage but also to maintain and reserve the environment (Karoun and El-Mourid, 2009). Farmers are required to be motivated in order to increase water productivity through technical assistance, capacity building and the right incentives and policies (De Fraiture and Wichelns, 2010). Improving crop water productivity relies not only on water management, but it involves a range of practices. Ali and Talukder (2008) summarised the techniques and practices that can be use to improve water productivity. These include: deficit irrigation, proper sequencing of water deficit, surge irrigation in vertisol, increasing soil fertility, improving harvest index, manipulation of seedling age, wet-seeded or directed seeded rice, priming or soaking of seed, application of organic matter, tillage and sub-soiling, water harvesting, minimising the transpiration, water saving irrigation, crop selection, modernisation of irrigation system and integrating agriculture-aquaculture.

## EXAMPLES OF METHODS FOR ENHANCING WUE

**Increasing harvest index:** The harvest index is the ratio of the economic yield to total biomass of a given crop and all agricultural systems are interested for the useful part of the crop; e.g., grains, seeds, fruits, vegetables and so on (Boyer and Westgate, 2004). The economic yield is very sensitive to the water balance in the plant and particularly during the reproductive stages. For example, water deficit conditions during germination (Boutraa *et al*., 2009) or early stages of plant growth result in early senescence (Boutraa and Sanders, 2001a, b), which result in reducing grain filling and consequently yield loss (Yang *et al*., 2001; Ali, 2006). Water stress can affect plant reproduction and it causes ovary abortion (Boyer and Westgate, 2004), or pollen sterility (Saini and Westgate, 1999). Improvement of harvest index by increasing the rate of grain filling and accelerating the mobilisation of photoassimilates may improve water use efficiency in water scarce environments (Zhang and Yang, 2004; Ali, 2006).

**Deficit irrigation:** Deficit Irrigation is the application of only predetermined percentage of calculated potential water use. This method needs the use of remote sensing techniques that can detect and assess the level of plant water stress and the amount of water needed by the plant. This technology uses the plant as an indicator, to assess the plant water requirement rather than soil water status (Jones, 2004a, b). This method can greatly reduce the amount of water used by the plant and has the potential increase of WUE. The Deficit Irrigation can also save water by reducing the irrigation depth by watering only the plant root zone and increasing the interval between successive irrigation. For example, at the International Center for Agricultural Research in the Dry Areas (ICARDA) application of only 50% of full irrigation requirement causes a yield reduction of only 10-15% (Zhang and Oweis, 1999). Deficit irrigation has been successful in irrigation of fruit and vineyards (Fereres and Soriano, 2007; Chaves *et al*., 2007; Collins *et al*., 2010) and annual crops (Kirda *et al*., 2007; Wang *et al*., 2010).

## EXAMPLES OF SUCCESS STORIES

Crop varieties continue to be released through crop breeding programs, with yield improvement in water shortage environments, particularly in cereals (Morison *et al*., 2008). Several workers reported that about half of this improvement is due to the crop improvement and half due to improved agronomy and management (Passioura, 2002; Richards, 2004; Turner, 2004; Slafer *et al*., 2005). Results of a recent study by Nangia *et al*. (2008) showed that water productivity of maize, in terms of mass of crop yield per unit of evapotranspiration (WPET), can be improved with additions of nitrogen fertilizer. This improvement is highest at low levels of WPET associated with low to medium application rates of nitrogen. Beyond a threshold, further nitrogen application leads to little improvement in WPET. In Australia, one of the best examples is the release of wheat lines with high TE values. The wheat variety drysdale is well adapted to low-medium rainfall zones in Australia (CSIRO, 2008).

## CONCLUSION

Due to increasing demand for food production worldwide, in regions where water is scarce, the improvement of agricultural water production became an urgent need. As irrigated agriculture remains vitally important as a means of food production, enhancing water use efficiency is one of the main approaches to make better use of water. Many options to improve water use efficiency are available and the target is to produce yield with possible minimum amount of water. Despite the progress achieved in improving yield per unit of water used, major efforts still needed to deal with water shortage in order to increase food production and particular in regions where water is scarce. This goal can not be achieved without collaborative efforts between agronomists, plant physiologists, hydrologists, molecular geneticists, agricultural engineers, water experts and decision makers. The final aim of improving WUE in irrigated agriculture is to increase the economic crop product per unit of water in water scarce environments. The effective use by the crop of a limiting water supply can be achieved by manipulating crop penology or by using agronomic techniques and practices that can improve water use efficiency.

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