THE AGRICULTURAL WATER SUPPLY CHALLENGE - THE NEED FOR IMPROVED WATER USE EFFICIENCY

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Abstract

This paper examines the challenges of water supply in agriculture, with particular emphasis on requirements of field crops, including maize. It places the issue of water supply to agriculture in the context of increasing demands for water from alternative uses, declining quality of water, pressure of increasing population, all of which are placing stresses on water availability at local, regional and national levels. The paper also examines existing freshwater resources and the potential impact of climate change on water supply and distribution and consequential impact on water stress incidence in various parts of the globe. It examines competition for water in both industrialized and developing countries, with particular emphasis on the impacts on agriculture and food supplies. The challenge of water use efficiency (WUE) in agriculture is explored with discussion of agronomic, economic and physiological WUE concepts, with specific reference to maize.

Introduction

Plant growth and productivity are limited in many regions of the world by water deficit, and crop production has been more and more dependent on irrigation water supply. For example, the near tripling of the world grain harvest from 1950 to 1990 was associated with a 2.5-fold expansion of irrigation (Brown 1996). In the face of mounting population pressure and rapid industrialization, the demand for water for irrigation, industrial and residential uses continues to expand and competition between countryside and city for available water supplies has emerged and intensified. The demand for water is expanding beyond the sustainable yield of aquifers and is draining some of the world's major rivers dry before they reach the sea. Consequently, water scarcity must be considered to be a long term constraint to productivity, and enhancing water use efficiency (WUE) in crop production as an ongoing challenge. The current paper will review water supply, and examine the concept of WUE, and emphasize ways to improve WUE in maize production.

The agricultural water supply challenge

Water supply

Only 2.5 to 3% of global water is fresh and directly suitable for the maintenance of human life. The hydrological cycle is made up of a number of components and human society has historically made use of only some parts of the cycle, in particular snow, runoff from precipitation, soil moisture, groundwater and temporary storage in lakes or aquifers. The total amount of freshwater accessible from these sources for human use is only a very small proportion (about 1%) of the total amount of freshwater on earth, as much of the freshwater is trapped in permanent ice and snow of the ice caps. Nevertheless, the accessible volume of water is about 500,000 cubic kilometers in each year (Pereira 1973). However, there are signs that water resource availability is dwindling due to population growth and increased per capita water use (De Wrachien and Fasso 2002). According to the World Commission on Environment and Development, approximately 80 countries with 40% of the world population already suffer from serious water shortages (Hamdy et al. 2003).

Freshwater distribution

Freshwater resources are distributed very unevenly around the globe in both time and space (De Wrachien and Fasso 2002). Much of it is not located where the people want to use it. Some regions are hugely endowed with freshwater, while others have practically none.

Many regions of the world are already limited by the amount and quality of available water (Jackson et al. 2001). Sparsely populated Iceland, with 605,500 cubic meters of freshwater per person, is by far the world's water-richest country, followed by Surinam (453,000) and Guyana (282,000). At the other extreme, Kuwait, with only 11 cubic meters per person, Egypt (43), and United Arab Emirates (64) are the water-poorest countries. Canada (94,000), Norway (88,000), Russia (29,000), Sweden (20,000), and the United States (89,000) are well endowed with domestic water supply, but Italy (2,800), China (2,200), and the United Kingdom (1,200) are less well endowed (World Resource Institute 1998).

As a guide, hydrologists define water-stressed countries as those with annual supplies of 1,000-2,000 cubic meters per person, and if below 1,000 cubic meters, nations are considered water-scarce, with severe constraints on food production, economic development and protection of natural systems. For some large countries (population or area), like China, India and Australia the freshwater distribution within a country varies significantly, with vast areas being arid (desert and semi desert) or semiarid (including seasonally dry areas as defined in Williams et al. 1983) restricting food production, economic development and natural system protection. In the coming decades, climate change and a growing imbalance among fresh water supply, consumption, and population will alter the water cycle dramatically.

Impact of climate on waters supply

Considerable progress has been made in recent years in understanding the science of climate change. Atmospheric concentrations of greenhouse gasses such as CO_2, CH_4, N_2O have increased significantly since pre-industrial times, tending to warm the surface and produce other climate changes. Human activities such as fossil fuel use, land-use change, and agriculture are now considered responsible for these trends. Even recently, atmospheric CO_2 has increased from 315 mg L^{-1} in 1958 to more than 350 mg L^{-1} today, and it may exceed 600 mg L^{-1} by 2040 (Allen 1990), and doubling from the current concentration is predicted to occur in the next 50-80 years (Heisey and Edmeades 2000). According to the Intergovernmental Panel on Climate Change (1996), the global mean surface temperature has increased by about 0.3 to 0.6^{o}C over the past century, and based on its mid-range emission scenario and best estimate of climate sensitivity, an increase in global mean surface temperature of about 2^{o}C relative to 1990 is predicted by 2100.

Water resources have a close relationship with climate (Liu and Zheng 2004). A change in the global climate would have major impacts on aquatic ecosystems and both the quantity and quality of water available for human use. Warmer temperatures will accelerate the hydrological cycle, altering in uncertain ways the prospects for more extreme drought and/or floods. An increase in precipitation intensity resulting in more extreme rainfall events is a possibility. Arnell (2004) reported that climate change will increase water resource stresses in some parts of the world, including around the Mediterranean, in parts of Europe, central and southern America, and southern Africa; and that in other water-stressed parts, particularly in southern and eastern Asia, climate change will increase runoff in wet season. It is also believed that the hydrological changes are more speculative than the temperature projections (Arnell 2004).

Competition for water

There are three main water users: agriculture, industry and domestic. The largest user of water is agriculture, even in countries where irrigation is not common, accounting for 70 to 90% of consumption (Hamdy et al. 2003, Cai et al 2001, Goyne and McInyre 2003), the balance being used by industry (around 20%) or domestically (around 10%) (Sechler et al. 1999). Water demands continue to increase with population, incomes, and a growing application of services as well as by amenities such as streams, lakes and other aquatic systems. Water supplies though, have not kept pace with the growth of demand in recent decades; future increases in withdrawals will be constrained by high costs and growing conflicts among uses, including environmental care, even in the absence of climate change (Frederick 1994). The prospect of a greenhouse-induced climate change introduces additional uncertainty about the future availability of water, and a warmer climate would add to water demands.

Irrigation is important to producing food for the growing human population and enhancing living standards. Construction of dams and wells has contributed to the increase in irrigation, but it is capital intensive, making irrigation a major focus of public investments by national governments and international development agencies. From 1950 until 1979, irrigation expanded faster than population, increasing the irrigated area per person by nearly one third. This was closely associated with a worldwide rise in grain production per person of nearly one third. However, since 1979, the growth in irrigation has fallen behind that of population, shrinking the irrigated area per person by some 7 percent (Brown 1996). This trend will undoubtedly continue and probably accelerate in future as overall water demand increases more rapidly than available supplies. Irrigation also has negative impacts including soil erosion, soil salinity, accelerated groundwater depletion and paradoxically raised water tables, all of which constrain agricultural production.

With rapid urbanization and industrialization of developing countries, especially the population giants China and India, water demand for urban and industry use will increase rapidly. Overall, the demand for industrial and urban water supplies is growing more rapidly than agricultural demand (Cai et al. 2001), and to satisfy the water demands for economically beneficial industrial and socially desirable urban uses, water supply for agriculture is expected to become more restricted. In some parts of the world, meeting growing urban needs is possible only by diverting water from irrigation. In China, for example, farmers have not been able to irrigate from reservoirs around Beijing so the water could be used to meet the city's soaring residential and industrial demands. Those requirements are heightened by the population's growing affluence, which increases per capita water use as more homes and other buildings are connected to a reticulated supply and have indoor plumbing (Patrick 1994).

The Yellow River, the mother river of the Chinese, which once provided plenty of water for irrigation and other uses now cannot meet demand. It first failed to reach the ocean in 1972, now runs dry for progressively longer periods each year. In the late spring of 1996, it failed to reach the major food producing province, Shandong, and the situation is becoming progressively worse, partly due to the frequency of dry years. The big loser in the eight provinces along the river will be agriculture. As scarcity deepens, priority will be given to satisfying the needs of industrialization and urbanisation (Patrick 1994). Similarly, for the Murray-Darling River system in Australia (Young 2001) and many rivers in the United States (Tarlock 2001), stream flows have declined and competition for water among agricultural, urban, industrial sectors and environmental sectors has emerged, and some previously permanently or near permanently flowing streams have become ephemeral. In Australia, concerns with the Murray–Darling basin and other river and underground water resources have led to the National Water Reform agenda that concentrates on environmental, economic and social sustainability (Department of Prime Minister and Cabinet 2005), and Murray Darling Basin Commission (MDBC) conferences for young people on the health and sustainability of river ecosystems and communities that depend on them (MDBC 2005).

It is believed that water will be a major constraint to agricultural production in many countries in the coming decades, particularly in Asia and Africa. Major soci-economic adjustments and modifications to agricultural production systems will be required. However, if shortages in food emerge, they will pose serious challenges that may exceed the economic and political capacity required for the necessary adjustments to allocation and use of water in all sectors (Hamdy et al. 2003). A "soft path" to address water scarcity, focusing on increasing overall water productivity, is recommended (Rijsberman 2004). Some strategies have been recommended for possible solutions to the scarcity scenario, including water resource protection, price-adjusting policy, and improving WUE in all water consumption sectors (Otieno and Ochieng 2004, Popova and Kercheva 2004, Duke and Ehemann 2004).

The concepts of water use efficiency

Under the conditions of growing demands and intensifying scarcity of the freshwater, achieving high WUE will become a priority. There are different concepts of WUE according to the approach being taken, for example, economic, agronomic, and physiological. WUE should be managed comprehensively in relation to all water related developments (Milburn 1997).

Economic water use efficiency

When supply is non-limiting, its value is often neglected, but when scarce, the fact that it is an economic good having economic value to competing uses cannot be avoided. Economics has been described as the science of allocating scare resources among alternative goals. In contrast to the diminishing per capita resources available, global demand for water is rising. Consequently, water resource planning and management must take into consideration both the vertical and horizontal linkages of water to the other sectors and components of the economy to maximize net benefit from water allocation. It is essential to have a comprehensive and integrated procedure to formulate a strategy for sustainable water development and the management of available water resources for economic and environmental benefits.

Although urban areas and industrial enterprises worldwide have used water inefficiently, inefficiency of use in agriculture is a major concern to agriculturalists and water planners alike. Overall, agriculture consumes about 75% of the world's fresh water supplies, and in some places the fraction is considerably higher; for example, in Africa agriculture may use as much as 88% of the continent's water (Xie et al. 1993). However, the overall efficiency of agricultural water use worldwide is only about 40-45% (Postel 1992, Hamdy et al. 2003), implying that more than half of all water used in agriculture fails to contribute to production. Even small improvements in agricultural WUE through improved delivery systems that reduce losses by, for example, evaporation, seepage, and percolation beyond the root zone, would release substantial volumes for other uses. Further, modified crop production practices and selection or breeding for improved WUE by the crop plants themselves would have a large impact because of the dominance of agriculture in the world's water economy. Such improvements are essential both to maintain growth in agricultural productivity without additional sources of water and to allow scarce water resources to be allocated to urban and industrial uses as well as agriculture. Therefore, an increase in the agricultural WUE is the key approach to mitigate water shortages (Cai et al. 2001) and to reduce environmental problems. However, this should not be taken to mean improvement in WUE elsewhere is not needed - potential exists for saving water in industrial and urban sectors – the review of Cai et al. (2001) provides substantial discussion of potential policy frameworks and consequences for the various stakeholders.

Agronomic water use efficiency

From an agronomic viewpoint, WUE is usually a seasonal value defined in terms such as:

$$\text{WUE} = \frac{\text{yield per unit area}}{\text{water used to produce yield}}$$

WUE is mostly calculated by combining soil surface evaporation and crop transpiration as evapotranspiration (*ET*). Actual evapotranspiration of field grown plants (ET_a) is either equal to or less than maximum evapotranspiration (ET_m), which occurs under conditions where soil fertility is non-limiting, plants are free of disease and pests, and soil water status does not limit plant growth. Usually, ET_a is less than ET_m and therefore plants experience deficient evapotranspiration (ET_d) and actual crop yields (Y_a) are less than potential maximum yields (Y_m). Deficient evapotranspiration has different effects on crop yields depending on the stages of crop development at which the deficit occurrs and the sensitivity of the crop species to short term or prolonged water deficit. High WUE means plants produce more biomass or higher yields per unit of water consumed. Crops that need non-limiting water to produce high yields include rice, wheat, maize and soybean but others such as sorghum and millets are less sensitive to water stress and produce relatively high yields even when water stress occurs. Nevertheless, WUE by maize is about 2.5 times that of soybeans under the same weather conditions (Yu et al. 2004), with current best practice producing around 20 kg grain per millimeter of water used per hectare (Passioura 2004). Examples of crop water use efficiency (CWUE, a similar concept to agronomic water use efficiency), expressed as yield per megalitre (ML) of evapotranspiration (ET) from sowing to harvest are presented for Queensland in Table 1. One weakness of expressing CWUE in terms of yield per ML of evapotranspiration is that the differing energy densities in crops are ignored. Though beyond the scope of this paper, it would be better to express CWUE (or agronomic WUE) as megajoules (MJ) of energy fixed per ML of evapotransipration, allowing more a valid, though conceptually different, comparison of WUE to be made. This, then, would account for differences in product, for example, oil of carbohydrate.

Table 1. Examples of crop water use efficiency in Queensland

Crop	Crop water use efficiency (t ML^{-1})	
	Mean	Range
Grain Sorghum	1.54	1.1 – 2.2
Soybean	0.54	0.4 – 0.8
Sunflower	0.59	0.4 – 0.8
Maize	1.94	1.2 - 4.5
Barley	2.25	1.2 – 3.7
Wheat	2.32	1.0 – 2.5

Source: Goyne and McIntyre (2002)

The higher CWUE for winter crops (eg barley and wheat) can be explained by the lower evaporative demand during the cooler months when these crops are produced.

Irrigation scheduling can be used to improve WUE, and various strategies may be adopted depending on the crop response to water stress, water holding capacity of the soil, the availability of irrigation water and the irrigation system used. Farming practices also affect WUE, because management can modify soil evaporation and transpiration, and regulate plant growth and development. Thus crop selection, coupled with optimized planting dates, plant population, fertilizer and weed management along with irrigation water management can increase crop WUE (Araus 2004, Panda et al. 2004). In Queensland, Goyne and McIntyre (2003) have examined changes to irrigation system characteristics that contribute to improved WUE, including application efficiency, evaporation, drainage and seepage mitigation and avoidance of waterlogging, and through addressing these, WUE in cotton has improved by over 10% from 2000 to 2002. Similar or greater improvements are likely to be achievable in other crops including maize. Passioura (2004) argues for improved water productivity as a means of increasing food production and reducing demand for increased land allocation to irrigated agriculture.

Physiological water use efficiency

Physiological water use efficiency relates plant photosynthesis to water consumption. Leaf stomatal opening for CO_2 uptake for photosynthesis results in an inevitable loss of water by the same process of CO_2 acquisition – gas diffusion. WUE is a parameter relating to the two fluxes and showing the total CO_2 fixed per unit water lost. It can be expressed as:

$$\text{WUE} = \frac{\text{mass } CO_2 \text{ fixed}}{\text{mass } H_2O \text{ transpired}} \qquad \text{mass basis}$$

$$\text{WUE} = \frac{\text{mol } CO_2 \text{ fixed}}{\text{mol } H_2O \text{ transpired}} \qquad \text{mole basis}$$

A related quantity is the transpiration ratio, which is the reciprocal of the WUE and hence represents the water lost per unit of CO_2 fixed. For typical plants in which the first stable product of carbon fixation is a three-carbon compound (C_3 plants), about 500 molecules of water are lost for every molecule of CO_2 fixed by photosynthesis, giving a transpiration ratio of 500 (the corresponding WUE is 0.002). The large ratio of H_2O efflux to CO_2 influx results from three factors – the concentration gradient driving water loss which is about 50 times larger than that driving the influx of CO_2, CO_2 diffuses about 1.6 times more slowly through air than water, and finally CO_2 uptake must cross the plasma membrane, the cytoplasm, and the chloroplast envelope before it is assimilated in the chloroplast, the three membranes adding to the resistance of the CO_2 diffusion pathway.

Some plants are adapted for life in particularly dry or seasonally dry environments. These plants, designated the C_4 and CAM plants, have different photosynthetic pathways for fixation of CO_2. Plants with C_4 photosynthesis generally transpire less water per molecule of CO_2 fixed. A typical transpiration ratio for C_4 plants is about 250. Desert-adapted plants with CAM photosynthesis have even lower transpiration ratio - values of about 50 being relatively common.

Nevertheless, variation in photosynthetic capacity among cultivars of maize are known and can be affected by farming practices (Campos et al. 2004, Kang and Zhang 2004), for instance nutrient supply (Muchow and Davis 1988).

Even for the same group of plants or the same plant species, the transpiration values are quite different. Transpiration ratios for C_4 plants are typically in the range of 200 to 350, while for C_3 plants values well above these are cited (Jensen 1973). The low transpiration ratio for C_4 plants reflects their capacity to maintain high rates of photosynthesis while effectively conserving water. The WUE differences among plant species provide options to grow water stress-adapted plants according to the water supply in a given region. This may point to the use of more C_4 and CAM photosynthetic pathway crops. Changes in temperatures predicted for 'greenhouse climates' would imply that the adaptive range of C_4 plants, principally tropical grass species will increase. For instance, under greenhouse climates, the area in southern New South Wales may have a climate similar to present day Central Queensland (Birch et al. 2000), making it potentially more suitable for C4 crops. Whether this change occurs depends on more than just climate and water supply, but on other elements of the agricultural production system, in particular soil and soil water holding capacity. In addition, changing the edaphic features of crop plants to improve their WUE needs to be considered and is canvassed in a companion paper (Huang et al. 2006, these proceedings).

Conclusion

The available fresh water is limited in many parts of the world. A multiplicity of factors, such as climate change, population increase and economic development leading to greater affluence of people will increase the competition among agriculture, industry and urban uses and environmental care for available fresh water supplies.

Though potentials for improving WUE exist in all water consuming sectors, the greatest potential savings can be made in agriculture. The reason is clear - agriculture consumes by far the largest portion of fresh water, so small improvements of WUE can have a significant effect on water availability to other sectors.

Irrigation methods and systems, planting regime, plant improvement and selection of crop species and use of appropriate agronomic practices are the main factors likely to lead to improvement in WUE, and are covered for maize in a companion paper (Huang et al. 2006, these proceedings). Maize as a C_4 crop plant, has an advantage in CO_2 fixation, and will play a more important role in increasing WUE.

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Improving the efficiency of water use in agriculture will also depend on matching of improvements main system (off-farm) with appropriate incentives for on-farm investments aiming to improve soil and water management. Such options will require improved water delivery systems to provide adequate on-demand service as well as use of advanced technologies (i.e. soil moisture sensors and satellite evapotranspiration measurements) to improve efficiency and productivity of water in agriculture. Resolving the challenges of the future requires a thorough reconsideration of how water is managed in the a... Agricultural Water Use in California: A 2011 Update is a thorough review of published research and technical data as well as State of California publications to assess the overall potential for agricultural water use efficiency to provide new water supplies. The report found that little potential exists for new water unless large swaths of agricultural land are taken out of production, which technically is not water use efficiency.Â â€¢ Previous reallocations of agricultural water supplies for environmental purposes represent at least 5 percent of farm water diversions depending on water year.Â The DH Report analyzed the potential for improved onâ€farm irrigation efficiency to decrease Improving water-use efficiency will require simultaneously applying various water-saving and water-optimizing approaches. Finally, the chapter identifies research and societal barriers that may impede progress in increasing water-use efficiency.Â For many regions in the United States, the current methods of agricultural water use are unsustainable. For example, groundwater aquifers store rainwater for the future, but in some locations and during periods of prolonged drought, groundwater is extracted at a faster rate than it is recharged.Â A major challenge for better water management is planning and preparedness for the high levels of spatial and temporal variability of conditions that affect water-use efficiency, such as climate variability.