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Blue Water Demand for Sustainable Intensification

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ABSTRACT

The agricultural challenge of meeting global food demand requires an increase in the level of agricultural water productivity and some increases in global water use. But many arid or semiarid agricultural regions of the world are facing declining water availability for irrigation. Examples of declining groundwater availability are seen throughout arid and semiarid areas of North America, Africa, and Asia. Relevant to water demand for sustainable intensification of agriculture, this paper touches on concepts where policy can work toward improving water productivity, including: (i) assessing crop water use and productivity, (ii) promoting cultural practices for increasing crop water productivity, (iii) improving efficiency of green water use, and (iv) protecting agricultural water supplies. Developing a paradigm of assessing crop water productivity and comparing with potential water-limited yields is a valuable diagnostic tool leading to improved management and water use. Similarly, water footprinting is a water accounting tool that should be applied toward improvements in agricultural water productivity. These assessment tools can prioritize how and when agronomic practices and plant genetic improvements can best be employed. This paper also overviews some cultural practices that can improve water productivity in dryland, rainfed, and irrigated systems. Several examples of policies that influence the supply of water for irrigation are given. Innovative policy structures are needed that allow sharing of water among agricultural, municipal, and environmental users while also rewarding conservation and efficient use. Specific policies that are designed to protect water supplies for agricultural use are needed.

The challenge of meeting global food demand is frequently discussed, but the critical role of agricultural water security is often left out of the discussion. Globally, irrigated crop production accounts for 36% of food production on 16% of total cropland. To emphasize the importance of surface and groundwater resources used for irrigation, these resources are referred to as "blue water." Blue water differentiates irrigation water from "green water," the water used by crops from precipitation. This differentiation allows science and policy to focus on water resources that have the higher cost of use and development. While the focus of this paper is on the demand for blue water, in a cropping system blue water cannot be separated from green water because both are complimentary and can be substituted for each other. Increasing global food production requires securing the blue water resources currently used by irrigated agriculture, developing additional water resources, and improving the use efficiency of both blue and green water sources.

Many arid or semiarid agricultural regions of the world are facing declining water availability for irrigation due to groundwater decline, increasing competition for water by municipal and industrial users, drought, and climate change. For example, the central and southern Great Plains of the United States was highly developed for irrigation in the mid-20th century with irrigation wells tapping the underlying Ogallala Aquifer. Irrigation development has led to declining water levels in the aquifer. While the decline is <10% of the original water storage, there are some southern areas of the aquifer where only about half of the original saturated thickness remains, leading to estimates that 35% of the southern High Plains will not be able to economically pump water for irrigation within 30 yr (Scanlon et al., 2012). Another example of irrigation driven groundwater decline is in central Punjab, India, where rates of decline increased from 18 cm yr^{-1} in the early 1980s to almost 1.0 m yr^{-1} by 2005 (Kahlon et al., 2012). This decline has been driven by a rapid growth in the number of unregulated irrigation wells. Similar groundwater decline is apparent in arid and semiarid regions throughout the world (Algheriani, 2007; Basch et al., 2012; Kahlon et al., 2012). Competition for blue surface water resources also threatens availability of water for irrigation. For example, in the U.S. state of Colorado, urban demand for water is expected to drive a loss of 175,000 ha of irrigated farmland by the year 2030 (Colorado Water Conservation Board, 2004) and losses of similar magnitude are occurring in other western U.S. states.

In these examples we see that trends in blue water availability for agriculture are opposite increasing water required to meet global food demand. Long range planning and policy are needed to secure the availability of blue water resources for sustainable increases in food production. In addition to securing

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access to blue water resources, continued support for agriculture approaches that increase crop water productivity are needed. Crop water productivity can be defined as the amount of crop produced with the green and blue water resources used ("crop per drop"). Rockström et al. (2009) suggested that without improvements in crop water productivity, global food demand would drive the need for a 60 to 70% increase in cropland. Key questions surrounding the need for increased water productivity are: how can crop water productivity be improved? Where and when will increased water demands occur? How much water will be needed, and how can future agricultural water needs be secured? These questions must be considered in a policy context where water is also prioritized for increasing demand for municipal, industrial, and environmental uses.

This paper addresses several key issues to be considered in a policy context related to water demand for sustainable intensification of agricultural systems. These include: (i) tools for assessing crop water use and productivity, (ii) cultural practices for increasing crop water productivity, (iii) improving efficiency of green water use, and (iv) policies that influence agricultural water supplies.

ASSESSING CROP WATER USE AND PRODUCTIVITY

A starting point for increasing crop water productivity is establishing a paradigm for assessing it. Agriculturists are accustomed to assessing crop yield on a land productivity basis (kg ha^{-1}), but it is less common to evaluate crop water productivity, the crop yield per unit of water used (kg m^{-3} or kg ha^{-1} mm^{-1}). Similarly, the more common measure of agricultural water use is based on diversion of blue water rather than on actual crop water use, including green water use. Assessments based on diversion rates do not allow separation of irrigation efficiency and crop water productivity. Quantifying and evaluating water productivity can empower change in agronomic management that will lead to improvements.

To illustrate the concept of crop water productivity, consider a relationship of grain yield to evapotranspiration for maize (*Zea mays* L.) in a U.S. Great Plains environment (Fig. 1A). The positive, linear relationship, called the water production function, illustrates the potential water-limited grain yield under optimum management in this environment. The slope and intercept of the water production functions vary with crop species and environmental conditions, but in all cases the slope is positive, meaning that increasing yield under optimum management requires increased water use by the crop. In many cases, however, actual production falls below the line of potential yield due to other limiting factors such as poor planting or emergence, poor soil fertility, competition from weeds or disease, or other crop damage (Fig. 1A). In many such cases, improved agronomic management can achieve yield increases without increasing demand for water, thus leading to improved water productivity. Developing a paradigm of assessing production levels as a function of water use and comparing with lines of potential water-limited grain yields can be a valuable diagnostic tool leading to improved management and water use (Passioura, 2006).

The slope of the water production function is an indication of the biological efficiency of the crop in converting water into grain, while the *x* intercept indicates the amount of water used in evapotranspiration before the initiation of grain formation. Practices that reduce direct evaporation from the soil, such as conservation tillage or subsurface drip irrigation, can shift the intercept to the left (Fig. 1B), resulting in increased production without additional water use. While improved management can lead to production that achieves the water limited yield and minimizes evaporation, it has little influence on the slope of the water production function. The slope of the water production function for a given biomass crop is very stable over management changes (Tanner and Sinclair, 1983). The slope of the line may, however, be improved through plant genetic improvement (Fig. 1C). Thus, a combination of agronomic management and genetic improvements are needed to improve crop water productivity (Passioura, 2006). Developing a paradigm of assessing crop water productivity can aid both managers and plant breeders in the effort. For some irrigated regions, quantifying water consumption by the crop is not common and additional resources are required to obtain this information. Quantifying water use in a production system can take a crop water balance approach, requiring measurement of irrigation, precipitation, and soil water changes over time. In some cases, these values can be estimated indirectly through remotely sensed data in the visible and thermal parts of the electromagnetic spectrum (Steele et al., 1994, Taghvaeian et al., 2012). Assessing spatial variability of water use and yield can facilitate precision water management.

Another tool that can guide water management decisions towards sustainable intensification of agriculture is water footprinting (Hoekstra et al., 2009). Water footprinting is a

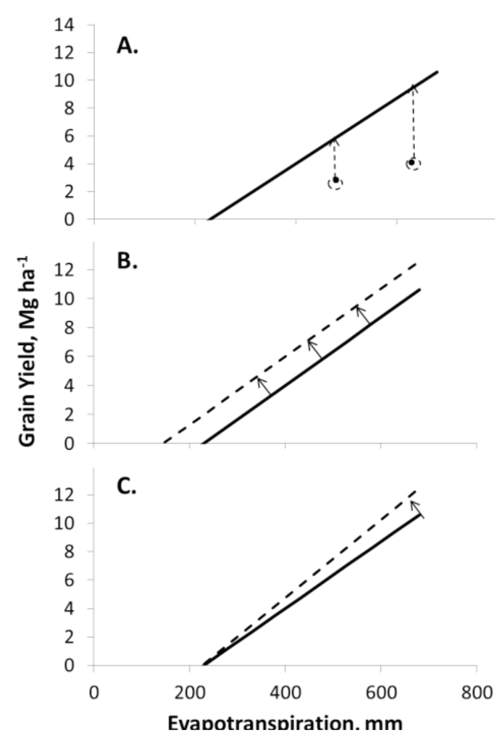

Fig. 1. Plot A: Water production function of maize in the Central Great Plains of the United States (based on Nielsen et al., 2011); Plot B: Management practices that reduce direct soil evaporation shift the *x* intercept to the left but do not affect the slope; Plot C: The slope of the water production function is modified through improvements in crop genetics. Assessing crop water productivity can aid both managers and plant breeders in efforts to improve water productivity.

water accounting approach that evaluates the total volume of water used in the production chain of a product. It separately categorizes water used from precipitation ("green water"), surface and groundwater resources ("blue water"), and the impacts on water quality ("gray water") and combines the components for the total water footprint. The blue water footprint is most relevant for areas of the world where surface and groundwater resources are used for irrigation. The blue water footprint is the total use of surface and groundwater resources used in producing, processing, and transporting a product. It includes evaporation, transportation, water losses from a catchment or incorporation into the product. For products derived from irrigated crops, evapotranspiration is the dominant component of the blue water footprint. Many scientific publications (Jefferies et al., 2012; Mekonnen and Hoekstra, 2011) and popular science outlets (National Geographic, 2010) have highlighted the water footprint of agricultural products, but few have used the potential of water footprinting as a tool to evaluate how efficiency and productivity improvements integrated throughout the production chain could be combined to reduce the water footprint of an agricultural product. For example, the water footprint of a meat product is dominated by the water consumed by crops used for animal feed and is influenced by a large number of management decisions made in the production process. Using the water footprint approach can individually or collectively assess how changes in tillage or irrigation practices, feed crop selection, diet formulation, and marketing approach affect the overall efficiency of water use for the meat product. Applying the water footprinting approach in this manner can help direct resources toward the most important ways for improvement in agricultural water productivity.

Cultural Practices for Increasing Crop Water Productivity

A variety of cultural practices can be employed in irrigated crop production systems specifically to improve crop water productivity. In general, practices that improve crop vigor can improve crop water productivity (Passioura, 2006). These approaches can be coupled with improvements in crop genetics to help meet increasing blue water demand. Critical practices include control of weeds, pests, and diseases that reduce yield. A few other common cultural approaches that influence water productivity are highlighted here:

- Conservation tillage. Crop residues managed with conservation tillage systems can be an effective means of reducing loss of soil water to direct soil evaporation. Further, crop residues can reduce losses of water due to runoff from intense precipitation or heavy irrigation. In irrigated systems, conservation tillage can delay the time of the first needed irrigation by capturing and retaining off-season precipitation. Improvements in capture and storage of precipitation (green water) from conservation tillage can reduce crop demand for irrigation (blue water), resulting in an increase in the ratio of green water/blue water use by an irrigated crop.
- Micro-irrigation/Drip Irrigation. Micro-irrigation systems, including surface or subsurface drip irrigation (Lamm et al., 2012) can carefully control the timing and amount of applied water to reduce deep percolation, evaporation, and runoff losses. By applying water in the immediate root zone of the crop, the uptake and use of the water is more efficient. The abilities to use chemigation and precision nutrient management are further advantages for drip irrigation systems. In one U.S. Great Plains study, irrigation requirements were reduced by 25% using subsurface drip irrigation compared with sprinkler irrigation without any loss in crop productivity (Lamm and Trooien, 2003).
- Limited irrigation. Irrigating to meet a crop's full ET demand often results in lower marginal water productivity than supplemental or deficit irrigation practices that target a smaller volume of irrigation towards critical crop growth stages. Specifically, limited irrigation practices avoid drought stress during anthesis, when the effects of drought on crop yield are most pronounced. Passioura (2006) anticipates that "as water for irrigated agriculture becomes scarcer, it is likely that full irrigation will be replaced by deficit irrigations targeted to periods without rain that coincide with especially sensitive stages of a crop's life."
- Precision irrigation. Site-specific irrigation management is a developing technology that allows for spatial and temporal control of applied irrigation (Kranz et al., 2012). Due to inherent spatial variability of soil and topography in agricultural fields, uniform irrigation across a field can lead to water shortages or losses. By precisely meeting the crop water demands according to the spatial variation of the field, water use efficiency is improved through reduced losses of water to evaporation, drainage, or runoff and avoiding localized water deficits. Precision irrigation control systems have already been developed and are commercially available, especially for self-propelled sprinkler irrigation systems, but there is need for further development of approaches to develop irrigation management zones and sensor systems for precision irrigation control.
- Water dynamic crop rotations. Crop rotations can be implemented to diversify crop water use patterns and increase efficiency. For example, inclusion of perennials and cool season annuals in rotations with summer annual crops spreads the peak irrigation demand of the different crops over time, avoiding deficits associated with peak demand of a single crop type. In many climates, cool season crops like winter wheat use a greater proportion of green water relative to blue water when compared to warm season crops like corn and therefore may be more compatible in water-short areas. Water productivity advantages can be gained from rotations of fully irrigated high value crops with low-input crops managed with limited irrigation or dryland (rainfed) production.
- Rainwater harvesting. In some geographic regions, improving ability to capture rain during wet periods has the potential to reduce demand on groundwater resources during dry periods. Rainwater harvesting structures can recharge aquifers and improve water storage in the soil. These structures include ponds, percolation tanks, check dams, stream bunds, and gully plugs. In many states in India, large areas of rain water harvesting have been successfully implemented (Kahlon et al., 2012).

IMPROVING EFFICIENCY OF GREEN WATER USE

Due to the many global limitations on blue water supplies for irrigation, the needed increase in global food production depends strongly on improvements in the use of green water resources (Basch et al., 2012). Increasing water productivity on the global scale must be seen as an integration of the crop water productivity in irrigated and rainfed systems (Rost et al., 2008). Two important examples of improving green water use are dryland systems and use of supplemental irrigation in humid regions.

In dryland systems, it is well documented that management practices can be employed to improve water use. For example, the Great Plains region of the United States is an area of widespread dryland crop production, with wheat being the dominant crop. The prevailing cropping system is a 2-yr rotation of wheat (*Triticum aestivum* L.) and summer fallow. The adoption of no-till practices has resulted in greater precipitation storage and use efficiency, which has led to greater cropping intensity, higher productivity, more diverse crop rotations, and improvements in soil properties (Hansen et al., 2012). In Colorado, for example, a no-till rotation of winter wheat–maize–fallow increased total annualized grain yield by 75% compared to winter wheat–summer fallow (Peterson et al., 2012). The no-till systems promote the capture and retention of water (Nielsen and Vigil, 2010; Peterson et al., 2012; Stewart and Lal, 2012). Similar observations of improved water productivity in intensified, no-till based dryland systems have been made in other environments (Schillinger et al., 1999; Li et al., 2000). When dryland systems improve the efficiency of green water use, there is no additional stress put on the limited blue water resources.

Irrigated agriculture development has historically centered on arid and semiarid regions, such as the western United States. However, in recent years, development of supplemental irrigation systems has intensified in more humid regions as an approach to stabilize yield variation. By avoiding season rainfall shortages, the supplemental irrigated systems improve overall efficiency of the use of the precipitation in these humid regions. Hoekstra et al. (2011) stated that "an important component of the solution to overexploitation of blue freshwater resources in water-stressed catchments is to increase water productivities in water-abundant areas."

Policies for Agricultural Water Security

A major issue associated with agricultural water security is a mismatch in the scale of water management and food supply. Water policies are local in scale and can externalize the effects of policy on geographically larger factors such as global food supply. In the United States, water rights are regulated by state governments. In many states, regulations are being enacted to address water scarcity issues or to enable water sharing between agricultural, municipal, and industrial water users. Commonly, these policies move water from agriculture to municipal and industrial sectors (WGA-WSWC, 2012). Several examples of current water policies illustrate how local policy may not emphasize global agricultural water security.

Policies in California have facilitated the transfer of irrigation water from the Imperial Irrigation District to the San Diego County Water Authority based on water saved from fallowing agricultural land (Jones and Colby, 2012). Between 2004 and 2008, 26,000 ha of highly productive irrigated land were fallowed to allow water transfer for municipal use (Imperial Irrigation District, 2008). The water transfers can be economically attractive to irrigators because municipal water users may pay a higher price for the water than can be gained through irrigation. However, the local market approach to water management externalizes the costs of significant decreases in crop production from this key agricultural region.

In Colorado, transfer of surface water rights from agricultural to municipal users is common. Local policy traditionally requires a permanent dry-up of the land associated with the water right. Population growth projections suggest that there will continue to be dry-up of many thousands of hectares of Colorado irrigation land (CWCB, 2004). A concern over this projected loss of irrigated land has motivated recent policy efforts that seek alternative water transfer approaches that avoid complete dry-up. A 2005 policy (Code of Colorado Regulations, 2005) enables agricultural water users to temporarily transfer water to a different user without permanently changing the water right. Known as interruptible supply agreements, the approach limits water transfers to 3 yr out of 10. They help meet growing urban demand for water without a permanent loss of irrigated land and are an example of a more flexible, water sharing policy. However, the policy does not prevent an ultimate shift of water away from agricultural production nor does is internalize costs associated with production declines.

In Nebraska, state law gives natural resources districts authority to enact local regulatory tools for protecting against ground water overuse. Due to water shortages, the natural resource districts for most of the North Platte, South Platte, and Republican River basins have enacted policies that restrict new development of irrigation wells and establish pumping allocations on existing wells. As an example, in the Lower Republican Natural Resource District, a rule was established in 2008 that mandates metering of existing irrigation wells and limits irrigation to a total of 11,400 m^3 ha^{-1} over a 5-yr period. This water allocation reflects a 30% reduction relative to past rates of irrigation. This allocation rule, in combination with other programs that curtail irrigation on some land, has reduced irrigation rates from 3300 m^3 ha^{-1} in 2003 to 1300 m^3 ha^{-1} in 2011 (Nebraska Association of Resources Districts, 2013). The most noteworthy aspect of this policy is that crop productivity in the region has not been greatly reduced (R. Klein, personal communication, 2013). Producers have adopted practices such as no-till systems and growth-stage-timed irrigation practices that have improved the efficiency of water use under limited irrigation. This illustrates that water policies can stimulate improvements in crop water management. Part of the success of these policies is that they allow flexibility in how the producer distributes the limited water in space and time. Similar pumping limits have been set in other states overlying the Ogallala Aquifer, although there is a lack of coordination among the states that share the use of the aquifer (Sophocleous, 2012).

There are also examples of regulating water in more humid regions. In Florida, the Suwanee River Water Management District identified that some water levels have fallen below critical levels and that actions are needed to reduce withdrawls. Current plans recommend enhanced agricultural water conservation incentives and outreach efforts to help farmers increase the efficiency of their water use. Water-use permits require agricultural users to develop and implement comprehensive water conservation plans that include best management practices and irrigation scheduling tools (Suwannee River Water Management District, 2010).

Some of these policy examples illustrate the benefit of incentivizing best management practices or facilitating water sharing among different users. However, none of the examples demonstrate efforts to increase water supplies for agricultural use. Assessing and improving crop water productivity has significant potential for addressing global food demands, but these approaches will not ultimately lead to the level of increased food production needed if there is a continued loss of water for irrigation. Collective actions are needed to align local water policies with securing agricultural water required to meet global needs. There is evidence that this idea is beginning to emerge in policy. A few state agencies have added review and evaluation processes that prevent water transfers from creating harmful impacts to environmental and economic values (WGA-WSWC, 2012). More such efforts will be crucial for protecting agricultural water security.

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