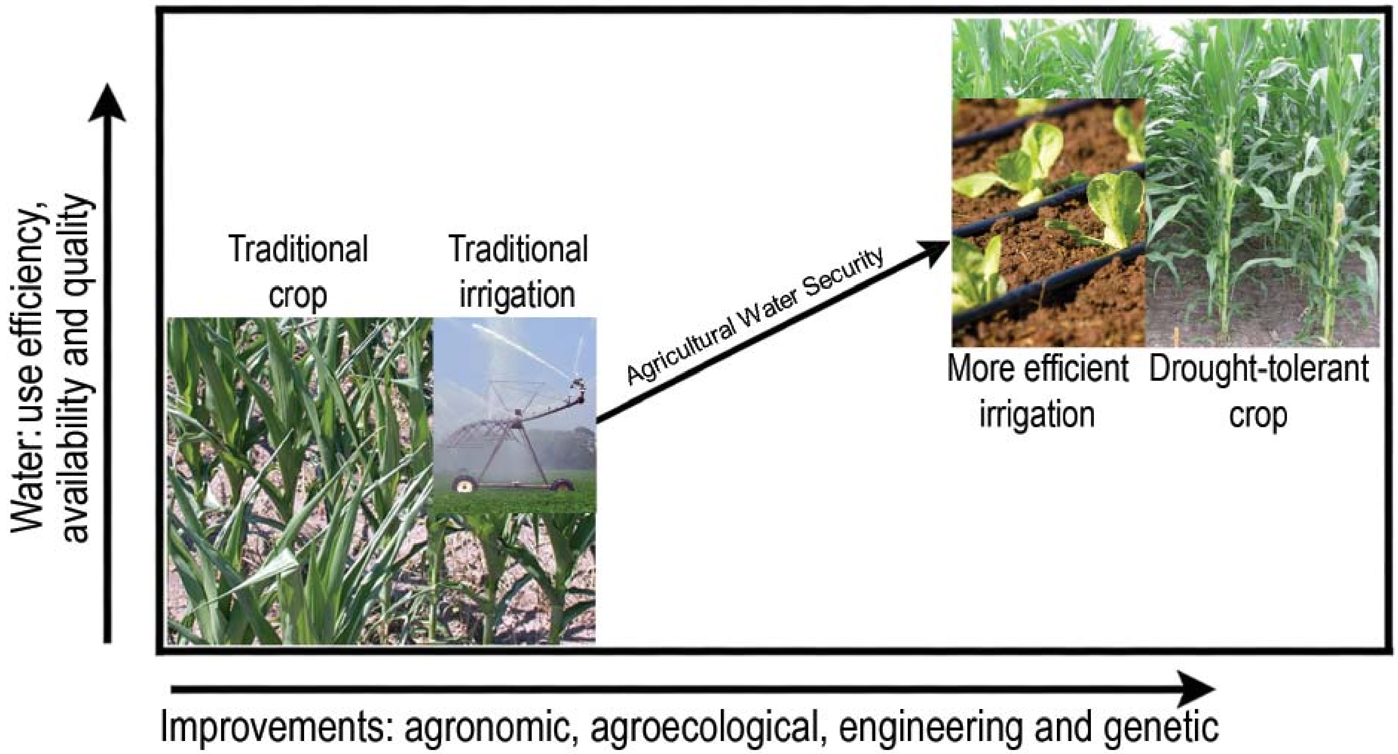
Agricultural Water Security: Research and Development Prescription for Improving Water Use Efficiency, Availability and Quality[1]



"Water is the staff of life."

—Traditional saying

"Our water crisis should occasion grave concern but not panic. We have solutions available; now we need a national commitment to pursue them."

—Robert Glennon (2009)[2]

[1] In Canada and the United States.

[2] Glennon R (2009) Unquenchable: America's Water Crisis and What To Do About It. Washington, DC: Island Press.

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Providing an open forum for exploring issues in agricultural biotechnology

December 31, 2010

The National Agricultural Biotechnology Council (NABC), a consortium of over thirty major agricultural research and educational institutions in the United States and Canada, has developed *Agricultural Water Security: Research and Development Prescription for Improving Water Use Efficiency, Availability and Quality.* This document outlines the challenges of agriculture's need for water (on average one liter of water for every Calorie of food consumed) and its impact on water quality. Research, development and implementation prescriptions are suggested for improving agriculture's eff ciency of use of water, expanding the supply of water for agriculture and reducing agriculture's impact on water quality.

NABC identif es water as a critical issue for agriculture. This document and NABC's annual conference in 2012 provide a summary and an open-forum report on needed action.

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Summary

The major and growing challenge for society is water. Water is essential for agriculture. Agriculture uses 70–80% of withdrawn fresh water. The global need by 2050 for increased food/feed production for 3.0 billion additional humans and for increased meat consumption in emerging economies coupled with the biobased industrial product opportunities will greatly expand agriculture’s need for water. Climate change also will impact water and agriculture. The effects of crop and animal production on water quality—nutrient and pesticide contamination and soil salinization—need to be reduced to meet increasingly stringent quality standards. Expanded, integrated, focused agronomic, agroecological, engineering and genetic research, development and implementation are essential to improve water-use efficiency, availability and quality as prescribed here for agricultural water security and food security for Canada and the United States.

Introduction

Water has always been an important issue for agriculture; it is now critically important. Improvements in water use and availability must be achieved to meet the food and feed needs of the projected 9.5 billion humans by 2050 and to provide biofeedstocks for the expanding biobased industrial products market. Simultaneously, agriculture's impact on water quality—via fertilizers, animal waste products, pesticides and salinity—must be reduced to meet the increasingly stringent water-quality standards. This paper outlines the water-related challenges faced by agriculture and identifies research and development opportunities for improving quality and increasing efficiency of use and availability, focusing on the United States and Canada [1]. Policy for water use (*e.g.* CAST 2009[2]) and changes by society and industry outside of agriculture are not addressed.

Challenges

Agriculture's Need for Water

Agriculture's need for non-saline water is huge, critical, and growing, as documented by the following:

- 70% to 80% of withdrawn fresh water is used by agriculture, whereas 20% to 30% is used by industry and directly by humans and municipalities.
- Yield of plant-based rain-fed agriculture is limited to a significant extent by less-than-optimal availability of water during the growing season, from brief spells of moisture stress to periodic major droughts. Optimum yield is restricted by up to 50% or more by limitations in water and solar radiation.
- Most plant species are highly inefficient users of water. Major crops—wheat, soybean, *etc.*—transpire through stomata over 150 molecules of water for each net molecule of CO_2 captured by photosynthesis.
- Food production requires large amounts of water. A rule of thumb is that 1–2 liters of water are used to produce one food calorie (Cal), *i.e.* about 500–1,000 gallons of water every day for an average daily ration of 2,500 Cals. However, the range is large. For example, production of 1 kg of wheat requires between 400–2,500 liters depending on variety, fertilization, moisture stress and management. This range of values provides hope for improvement in efficiency. Almost all of the water needed for meat and milk production is used to provide feed for livestock and is not directly consumed by the animals.
- Projected world population growth to 9.5 billion by 2050, coupled with increased meat consumption by people in emerging economies such as China, will greatly increase the need for water for food and feed production by agriculture; alternatively, dietary choices will be restricted by water limitations.
- Different agricultural production systems—*e.g.* large-scale traditional, genetically engineered crops, organic and locally produced—may require different prescriptions for improving water-use efficiency and reducing their environmental footprints, although the major water requirement for each will be for primary plant production and, therefore, similar.
- The United States and Canada—as exporters of corn, soybean, wheat, canola, *etc.*—are, effectively, major providers, not only of food and feed but also indirectly of water, to other parts of the world.
- Major new industrial product opportunities for agriculture, in the biobased or green economy, will require water to grow dedicated biomass crops—switchgrass, miscanthus, sorghum, algae, *etc.*—as well as for processing to fuels, chemicals and materials.
- Irrigation for agricultural crop production is essential in low-rainfall regions of the world, *e.g.* South Asia, the Middle East and North Africa. Although irrigation is used on less than 20% of agricultural land in the United States and even less in Canada, in some areas it is critical, *e.g.* the Central Valley of California, Arizona and the High Plains states. Half of the fruits and vegetables consumed in the United States come from irrigated fields in California. Years of increasing irrigation and urbanization are challenging water security in these areas. Groundwater aquifers are being depleted in the High Plains. Surface water sources are being fully used in Cali-

[1] Several *NABC Reports* contain presentations that address aspects of agriculture and water, *e.g. 16*, *19*, *20* and *21*. The 2012 conference will focus on agriculture and water.

[2] Council for Agricultural Science and Technology (CAST) (2009) Water, People, and the Future: Water Availability for Agriculture and the United States. Issue Paper 44. Ames, IA: CAST.

fornia and Arizona, such that agriculture is in growing competition with industrial, environmental and ecological, recreational and expanding urban users.

- Desertification is increasing globally, but almost exclusively outside of Canada and the United States.
- Global climate change is projected to have negative and positive effects on agriculture, depending chiefly on geographical location. Weather extremes will increase in intensity and frequency, including temperature and rainfall; some areas will become wetter, some drier. It is projected that southern latitudes will be less favorable for crop production whereas northern latitudes, *e.g.* the Canadian prairies, may be more favorable[1,2].

Agriculture's Impact on Water Quality

Agriculture, both intensive grain and animal production, has negative impacts on water quality as do industrial and municipal uses. Contamination of water—ground, rivers, lakes—with fertilizer, nutrients and other components of animal waste, and pesticides, is a problem. Salination is a byproduct of irrigation and fertilization.

- Fertilization is essential for high-yield grain production, *e.g.* corn and wheat. Up to 40% of fertilizer N (and other applied nutrients) are not taken up and eventually some enters rivers, lakes, groundwater and coastal waters, producing algal blooms and depleting oxygen levels. These hypoxic or dead zones are significant; in 2009, the hypoxic zone in the Gulf of Mexico was estimated at 3,000 square miles. The EPA has identified over 6,000 bodies of water in the United States, of which the quality is impaired by excessive nutrient content.
- Concentrated animal production—feedlots, large dairy facilities, poultry houses and swine farms—require management of waste nutrients and reduction of contamination of water.
- Pesticide, including herbicide, use—regulated by EPA in the United States and Health Canada's Pest Management Regulatory Agency in Canada—is standard practice for most plant agriculture. Weed control with herbicides eliminates the water lost to weed growth, and, similarly, pest control improves the efficiency of water use in food and feed production. Some of the early pesticides, *e.g.* the herbicide atrazine, were degraded only slowly and reached groundwater. Pesticide-detection systems have become highly sensitive and the significance of low-level, but now detectable, pesticide residues in water has become a controversial issue.
- Intensive irrigation and fertilization can increase the salinity of soil (and of groundwater), negatively affecting crop production.
- Erosion after conventional tillage leads to loss of topsoil to rivers causing contamination, not only with particulates, but also with agricultural chemicals carried by the soil.
- Water flows, necessary for ecological and ecosystem functions, directly compete with agriculture.
- Numeric nutrient water-quality standards for lakes, rivers and reservoirs are being developed and will increasingly impact agricultural production systems.

Although impacts by agriculture on water quality probably will never be completely eliminated, significant progress is being made, and this effort must continue.

The above challenges dictate expanded research and development efforts in Canada and the United States to increase water availability and use efficiency in agriculture and decrease adverse impacts on water quality.

Research and Development Prescriptions

Improving Agriculture's Water Use

The opportunities for improving the efficiency of water use by agriculture are genetic, agronomic including agroecology, engineering, and possibly chemical. Genetic approaches have significant potential with traditional plant breeding being supplemented with molecular genetic approaches. The first commercial product—drought-tolerant corn—is scheduled for farmers' fields in 2011. Agronomic and agroecological approaches are well established, *e.g.* conservation tillage and improved methods of delivering/managing irrigation water, but there is great potential for water savings through improved irrigation, management and other technologies. Chemical applications may mini-

[1] Eaglesham A *et al.* (Eds.) (2009) NABC Report 21: Adapting Agriculture to Climate Change. Ithaca, NY: National Agricultural Biotechnology Council.

[2] Bates BC *et al*. (Eds.) (2008) Climate Change and Water. Technical Paper VI of the Intergovernmental Panel on Climate Change. Geneva: IPCC Secretariat.

mize negative responses of crops to brief periods of water shortage.

Genetic, Agronomic, Agroecological, Engineering and Chemical Approaches

Research on the effects of abiotic stresses on plants, including drought, is increasing. For example, the *HARDY* gene, when expressed in rice, improves water-use efficiency by increasing photosynthetic assimilation while reducing transpiration; the *cspB* gene is an example from corn. Several plant-breeding companies have disclosed plans to market corn with increased drought resistance and improved yield stability. Industry will probably extend this initial breakthrough in improved water-use efficiency and drought tolerance to other major-acreage crops—soybean, wheat, cotton—whereas lower-acreage crops—barley, oats, horticultural products—will probably require public-sector R&D. In addition, public-sector research probably will be a major identifier of relevant genes to enable improved drought tolerance and increased water-use efficiency. Irrigation of perennial vine and tree crops will, in the near future, benefit more from appropriate timing of water applications than from genetics.

The above genetic examples of improved drought tolerance employed traditional breeding and selection of genes found in model plants or bacteria. Another genetic approach is to study species that are inherently more drought tolerant, such as sorghum. The genetic basis for sorghum's relative tolerance of moisture deficiency is being elucidated by comparison of its genomic sequence with those of more drought-sensitive plant species. A longer-term, more-high-risk possibility is to increase water-use efficiency by conversion of crops with C_3 photosynthesis—wheat, soybean, rice, *etc.*—to become C_4 photosynthesizers like corn and sorghum, although over thirty years of genetic and chemical attempts in this endeavor have been unsuccessful. However, the exploding, massive database and availability of new tools with more interdisciplinary approaches are reigniting this approach with the possible production of intermediate C_3/C_4 crops. A related approach is the study of the genetic and biochemical pathways of CAM species, *e.g.* the common ice plant (*Mesembryanthemum crystallinum*) and pineapple that have water-use efficiencies of up to ten times those of major crop plants. These plants absorb and store CO_2 during darkness and release it slowly during the day, thus reducing transpiration so that they thrive in hot, dry conditions.

Also possible is the development of crops that are grown at times when evapotranspiration demands are low. For example, rapidly maturing annual crops that are planted earlier or later would avoid maximum summer water loss.

Application of specific chemicals may mitigate the effects of drought. An example of a possible product is an ethylene inhibitor that protects plants from the effects of moderate moisture deficiency. Another example is stimulating production of the plant hormone abscisic acid to decrease stomatal opening, thereby reducing transpiration. A beneficial byproduct of future elevated atmospheric CO_2 levels will be increased stomatal closure, thereby reducing transpiration and increasing water-use efficiency.

Significant genetic variation in crop plants has been identified to reduce transpiration, such as waxy covering on leaf surfaces and more-efficient stomatal responses to water stress, and longer, more-branched roots and more-dense and longer root hairs for more efficient uptake of water and nutrients.

An advantage of abiotic-stress resistance versus biotic-stress resistance is that genetic and chemical solutions to abiotic stress should be long-lived, whereas resistance almost always develops to biotic stress products, both genetic and chemical.

The benefits from agronomic, agroecological and engineering-improved water use are well established and there is major opportunity for more in the future. Substantial contributions to date include:

- tillage modifications—from deep plowing to minimum till to vertical till or no till to improve soil structure,
- expanded use of cover crops,
- improvement in irrigation-water delivery and use from inefficient flood and furrow to precision irrigation, lined irrigation ditches, drip irrigation and micro-sprinklers,
- hydroponics for intensive vegetable production.

Potential future benefits include:

- soil-moisture sensing (*in situ* and remote) to guide management practices,
- mathematical modeling of crop-water requirements,
- precision agriculture,
- integrated cropping systems,
- management of complex soil water properties to enhance crop productivity,

- salt-water management in the root zone,
- irrigation technology including water-system automation to achieve water savings,
- irrigation water capture and reuse from development of new technologies and control systems,
- soil amendments for improved water-use efficiency, *e.g.* incorporation of long-lived biochar,
- drainage and water-quality management to improve water quality,
- integrated climate and land-use hydrologic-agro-ecological modeling systems for optimal location of agricultural lands in watersheds to maximize yield and natural assimilation capacity to minimize excess nutrients from agricultural production.

Some of the above will benefit both water-use efficiency and water quality.

Availability—Salt Tolerance and Reuse to Expand the Supply of Water for Agriculture

Fresh water constitutes 2% of the global supply, whereas 98% is saline. Development of crops tolerant of saline water is the major opportunity (for salinity); economically feasible desalination of water would hugely expand the supply of water for humans, but may still be too expensive for agriculture.

Land plants evolved from halophytes, but, in the process, lost their tolerance of salinity. However, there is significant variability in salinity tolerance of some crop plants, *e.g.* rice. Genetic approaches have increased salinity tolerance in tomato. Improving salinity tolerance of crops by 20% to 30% through traditional and molecular genetic breeding would have global impact, as productive acreage could be expanded and low-quality water employed for food production, allowing fresh water to be used to meet human and environmental needs.

Use of low-quality water, *e.g.* brackish or reclaimed water, for irrigation of feed crops and industrial uses represents an opportunity to expand the water supply for food production. Supplementing tree crops with low-quality water at certain times of the year is another possibility. However, water used to grow food crops, *e.g.* fruits and vegetables, must be safe at certain periods so as not to contaminate the harvested entity.

Research is needed to develop cost-effective wastewater and reuse options for suburban landscapes and agriculture. Sustainable water-management strategies will increasingly require more immediate reuse for all purposes.

Reducing Agriculture's Impact on Water Quality

Nutrient Contamination

Unused and waste nutrients from crop and animal agriculture can lead to contamination of rivers, lakes and groundwater. Nutrient management in crops is improving, *e.g.* corn used to require about 1.2 lb N fertilizer per bushel, whereas the current target is 0.75 lb. Fertilizer nitrogen delivery is being micro-managed to maximize crop recovery, driven in part by the need to minimize input costs. Geneticists are developing crops with increased nitrogen-use efficiency. In the long term, a high-reward/high-challenge research opportunity is self-nitrogen-fertilizing non-legume crops, thereby eliminating unused nitrogen and most of the nitrogen contamination problem in water from crop production. One revolutionary futuristic approach, potentially achievable with today's molecular tools is to induce crop plants to form ste*m no*dules containing rhizobia with photosynthetic capability (similar to those that nodulate the stems of Aeschynomene species*), thereby* eliminating the large energy draw from the plant to support biological nitrogen fixation in root nodules of today's legume and tomorrow's non-legume crops. In addition to the huge benefit to water quality, these would bring a major reduction in agricultural use of energy to synthesize fertilizer nitrogen.

Waste nutrients from animal agriculture are being recycled to soils under protocols that limit water contamination. Low-phytate plants, animals producing phytase—*e.g.* the Enviropig™—and phytase-supplemented feeds are being commercialized to reduce phosphate content in animal waste and minimize contamination of rivers and lakes.

Pesticide Contamination

Herbicide- and pest-resistant crops have less environmental impact on water, as well as direct reduction in water contamination by reduction in herbicide and insecticide sprays or use of compounds with faster degradation, *e.g.* glyphosate versus atrazine. A recent NRC report suggests that the major benefit from commercial transgenic crops is environmental[3], but the increase in gyphosate-resistant weeds is a concern.

[3] National Research Council (2010) The Impact of Genetically Engineered Crops on Farm Sustainability in the United States. Washington, DC: The National Academies Press.

Conclusion

There are multiple agricultural research and development opportunities to improve water availability, efficiency of use, and quality—genetic, agronomic, agroecological, engineering and chemical. Immediate, expanded, integrated and focused R&D investment by the public and private sectors—in genetics, chemistry, agronomy, agroecology and engineering—is our recommended prescription for agricultural water security and food security in the United States and Canada.

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