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Water for Agriculture: Global Change and Geographic Perspectives on Research Challenges for the Future

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In writing about the future of humanity on Earth, E. O. Wilson (2002) used the metaphor of a "bottleneck" to characterize the current and forthcoming period of tremendous human demand on planetary resources. The combination of continuing growth in global population, the associated demand for food and fiber, and a relatively fixed water resource base results in a number of grand challenges that will be part of the hydro-social research landscape for the next 20 years (Graedel et al. 2001, Myers et al. 2007, Robertson and Swinton 2005). Complexity of these coupled human-environment problems (Liu et al. 2007) and uncertainty in human understanding and responses to our transition into and through the bottleneck provide many opportunities for scholars to contribute relevant information on our adapting journey toward planetary sustainability (Frieman et al. 1999).

Research questions from earth system science, human-environment, and spatial perspectives that address uncertainties regarding future water availability, water quality, and how we will make use of water resources, are needed to help the world community find a way to support our growing planetary population. In the 2001 *Envisioning* report, the Water Science and Technology Board of the National Academies of Sciences identified 43 research issues (Table 1) among the three broad categories of water availability, water use, and water institutions, with some issues specific to the agricultural enterprise (Vaux, Jr. et al. 2001). A subsequent National Academies of Sciences assessment, discussing the role of research in addressing national water problems, indicated that research designs "should explicitly reflect the four themes of interdisciplinarity, broad systems context, uncertainty, and adaptation" (Vaux, Jr. et al. 2004: 6).

Recognizing that humans are greatly modifying the global water system the Global Environmental Change Programmes established an international effort that 1) informs policy but is driven by science, 2) is global in scope, 3) is interdisciplinary and integrative, and 4) addresses multiple time scales (Vörösmarty et al. 2004). The three framing questions regarding the global water system address the relative size of both anthropogenic and environmental changes, linkages and feedbacks that materialize due to changes in the global water system, and resilience and adaptability of management strategies. An ecosystem services approach to address fresh water resource issues provided a perspective for suggesting twelve priorities for updating water policies for the 21st Century (Postel 2005). In addition, Wilbanks and Kates (1998) have indicated that investigation of the local expressions of global change is a key contribution that geographers can make. This paper provides an articulation of research priorities that address water and agriculture for the next two decades, based primarily on a perspective that is informed by aspects of human dimensions of global change and geographic thought.

Water for Agriculture on a Changing Planet

Agriculture is by far the largest category of human use of available water resources. The 3,500 cubic kilometers of fresh water flows used by agriculture

Table 1. Research issues identified in the 2001 'Envisioning' report from the US National Academies of Science (Vaux, Jr. et al. 2001).

Water Availability
- Develop new and innovative supply-enhancing technologies
- Improve existing supply-enhancing technologies such as wastewater treatment, desalting, and groundwater banking
- Increase safety of wastewater treated for reuse as drinking water
- Develop innovative techniques for preventing pollution
- Understand physical, chemical, and microbial contaminant fate and transport
- Control nonpoint source pollution
- Understand impact of land-use changes and best management practices on pollutant loading to waters
- Understand impact of contaminants on ecosystem services, biotic indices, and higher organisms
- Understand assimilation capacity of the environment and time course of recovery following contamination
- Improve integrity of drinking water distribution systems
- Improve scientific bases for risk assessment and risk management with regard to water quality
- Understand national hydrologic measurement needs and develop a program that will provide these measurements
- Develop new techniques for measuring water flows and water quality, including remote sensing and in situ techniques
- Develop data collection and distribution in near real time for improved forecasting and water resources operations
- Improve forecasting the hydrologic cycle over a range of time scales and on a regional basis
- Understand and predict the frequency and cause of severe weather (floods and droughts)
- Understand recent increases in damage from floods and droughts
- Understand global change and its hydrologic impacts

Water Use
- Understand determinants of water use in the agricultural, domestic, commercial, public, and industrial sectors
- Understand relationship of agricultural water use to climate, crop type, and water application rates
- Develop improved crops for more efficient water use and optimize the economic return for the water used
- Develop improved crop varieties for use in dryland agriculture
- Understand water-related aspects of the sustainability of irrigated agriculture
- Understand behavior of aquatic ecosystems in a broad, systematic context, including their water requirements
- Enhance and restore species diversity in aquatic ecosystems
- Improve manipulation of water-quality parameters to maintain and enhance aquatic habitats
- Understand interrelationship between aquatic and terrestrial ecosystems to support watershed management.

Water Institutions
- Develop legal regimes that promote ground water management and conjunctive use of surface and ground water
- Understand issues related to the governance of water where it has common pool and public good attributes
- Understand uncertainties attending to Native American water rights and other federal reserved rights
- Improve equity in existing water management laws
- Conduct comparative studies of water laws and institutions
- Develop adaptive management
- Develop new methods for estimating the value of non-marketed attributes of water resources
- Understand use of economic institutions to protect common pool and pure public good values related to water resources
- Develop efficient markets and market-like arrangements for water
- Understand role of prices, pricing structures, and the price elasticity of water demand
- Understand role of the private sector in achieving efficient provision of water and waste water services
- Understand key factors that affect water-related risk communication and decision processes
- Understand user-organized institutions for water distribution, such as cooperatives, special districts, and mutual companies
- Develop different processes for obtaining stakeholder input in forming water policies and plans
- Understand cultural and ethical factors associated with water use
- Conduct ex *post* research to evaluate the strengths and weaknesses of past water policies and projects

represent 70 percent of global water withdrawals for human use each year (Holdren 2008). According to Postel and Vickers (2004), withdrawals of fresh water flows for agriculture can reach 90 percent in many developing countries. Agriculture is by far the largest consumer of available fresh water; it is estimated that water consumed in agricultural activities exceeds 90 percent globally (Food and Agricultural Organization 2002). Unfortunately, temporal and spatial variations in the climatically-driven delivery of water and the current status of the human response to these characteristics of the hydrologic cycle have 2.4 billion people living in "highly water-stressed areas" (Oki and Kanae 2006: 1069). According to Jury and Vaux, Jr. (2005: 15715), agricultural water use is not sustainable in many areas, "production may soon be limited by water availability," and market forces will likely result in a reallocation of water away from agricultural uses.

Humans now dominate Earth system functioning and global change. We have entered a new geologic epoch, the Anthropocene (Crutzen and Stoermer 2000, Zalasiewicz et al. 2008). And Steffan et al. (2004) suggest that we have domesticated the planet. Human domination of Earth ecosystems (Vitousek et al. 1997) is driven by the need for land to produce the food and fiber consumed by 6.7 billion inhabitants. "Together, cropland and pastures have become one of the largest terrestrial biomes on the planet, rivaling forest cover in extent and occupying ~ 40% of the land surface" (Foley et al. 2005). Human population grew rapidly during the 2nd half of the 20th Century and a Green Revolution in food provision, which resulted from agricultural intensification, meant that the volume of food available was able to keep pace with growing human demand. Increased production per hectare was a result of a mix of activities, including new crop varieties, irrigation, synthetic fertilizer, herbicides and pesticides, increased mechanization, and new and better use of information.

As our global population and food demand – both total and, potentially, per capita – continue to grow during the next two decades, there will be a significant need for additional food provision. That need for more calories and protein will require both more water and improved efficiency in agricultural water use. While forecasts vary, there are likely to be eight billion human residents sometime in the third decade of this century. This increase in global population is forecast to occur mostly in the less-wealthy countries with fewer financial and/or natural resources. It has been suggested that we have "progressed" into a no analog world (Mily et al. 2008); a world that has never experienced the types, rates, magnitudes, and scales of environmental change that the planet is currently experiencing.

There is considerable concern about water scarcity and water and food security issues. Rosegrant et al. (2003) identify a formidable challenge in meeting the demand for the world's increasingly scarce water supply and suggest that rainfed agriculture is key to meeting future needs for sustainable development of water and food. Postel (2000) noted that we are entering an era of water scarcity and proposed an effort to double productivity from water resources and reserve water for ecosystems; she suggested that accomplishing these goals will be "one of the most difficult and important challenges of the 21st century" (Postel 2000: 946). According to Tilman et al. (2001: 284), "If global population stabilizes at 8.5 to 10 billion people, the next 50 years may be the final episode of rapid global agricultural expansion." By extending the linear trends from the second half of the 20th Century, these authors noted that global irrigated area, an indicator of agricultural water demand, is forecast to be 1.3 times the current irrigated area in 2020, and 1.9 times as extensive in 2050 (Tilman et al. 2001). Although there are methods to increase water use efficiency, such as drip irrigation, crop breeding, and improving soil structure with manure additions, applications of such approaches vary. Tilman et al. (2002) noted that investment in technologies to improve water use efficiencies "is best facilitated when water is valued and price appropriately" (p. 674).

Accumulating Wealth and Changing Diets

Social drivers of change in food demand from agriculture include not only the number of humans (future population growth) but also changes in diet. Recent trends in protein sources for rapidly developing economies suggest that as humans

Table 2. Research questions in water for agriculture for the next twenty years.

1.	As we enter 'the bottleneck' with more people and fixed resources, how will we manage water to meet the global demand for food and fiber?
2.	Will there be an expansion of rain-fed cropland?
3.	Can we expand agriculture activities without loss of habitats, ecosystem services, and biodiversity?
4.	Is the nature of local agriculture intensification a result of expanded irrigation and/or increased efficiency?
5.	Are engineered systems changing from leaky to looped?
6.	Are there impacts on the local hydrologic cycle?
7.	Are local diets changing and, if so, what is the impact on water use efficiency?
8.	Are inequities in local water availability resulting in fewer calories per person, less meat consumption, etc.?
9.	Will global cooperation be able to provide a second "Green Revolution" and avoid major famine?
10.	How are the changes in agricultural water use impacting water quality?
11.	Has a sustainable pathway been found or is the local resource base being degraded?
12.	Is soil quality being maintained or improved?
13.	Are finite (fossil) ground water reserves being depleted?
14.	How well are soft-path approaches to water resource management working?
15.	Are local actions sustainable and do they assist with a global solution?
16.	What pathway to change are we on? And, is that pathway adaptable?

accumulate financial resources, they tend to change their diets to include sources of protein that require more water to produce (Myers and Kent 2003). Meat-based diets require much larger volumes of water per available calorie. Given limits on available cropland, agricultural yield growth is a very important need if we are to meet food and fiber demands without major investments in new agricultural lands. While an increase of 14 percent in global cropland is forecast by 2050 (Balmford et al. 2005), concerns exist regarding both where these new lands will be found and the loss of prime agricultural land around rapidly expanding urban areas. It will be important to monitor and quantify these changes at varying spatial scales during the next two decades. Agricultural intensification, whether through increasing the number of crops grown per year (double or triple cropping) or through increased Green Revolution technology, will be very important in efforts to avoid famine (Turner II and Ali 1996). In western Kansas, the use of increasingly more efficient irrigation technology exemplified the Green Revolution and has delayed the transition toward a return to an economy based on grazing large herbivores (or the so-called "Buffalo Commons" (Popper and Popper 1987)), but there are local issues with irrigation return flows and declines in water quality (Harrington and Harrington 2005).

Research Questions

Thinking about the challenges and changes for agriculture and water that are forecast for the next two decades (Table 2) inspires a number of research questions that address the multiple and complex factors that comprise the human dimensions of global change. Land change science concerns suggest the importance of topics related to changes in the location and amount of land allocated for specific uses and how changing social drivers will impact local decisions regarding land used for agricultural production. Another factor will be whether or not ideas from industrial ecology will help us with improving water use efficiency, especially in regards to irrigated agriculture. Ideas from the ongoing dialog in sustainability science and ecosystem services can inform questions that address how our demand for water will impact the resource base, the character of local solutions, how cultures identify with and address the need to move toward protein sources that require less water (or to reduce protein intake from what currently appears to be desired levels), and whether or not sustainable and adaptable pathways are being followed. Contemporary dialogs that include local food networks, organic agriculture, political ecology, and social inequity provide alternative lenses with which to view the ongoing changes in water and agriculture that will occur during the next twenty years. A spatial perspective will allow researchers to address how all of these issues arrange themselves in a complex configuration of places, cultures, and resource availability.

This essay has attempted to bring together much of what has been written about the subject of water and agriculture futures and issues for the coming decades. Water availability for agriculture presents considerable challenges and provides numerous areas for questioning that can be addressed by scholars from many different perspectives. Given the complexities of our coupled human-environment system and the uncertainties in how humans and their institutions will react to the concerns that have been identified, Table 2 identifies a sample of the types of questions about water and agriculture that can be addressed as our global community passes into the bottleneck.

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