FEDERAL RESERVE BANK OF KANSAS CITY

ECONOMIC REVIEW

Special Issue 2016 *Agriculture's Water Economy*

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Foreword

Consistent water availability is critical to agriculture. Farm production worldwide has evolved, to a significant extent, on the basis of consistent and reliable water resources, including both surface water and groundwater.

The water economy has been an area of interest to the Federal Reserve Bank of Kansas City for many years. In 1979, one of our first economic policy symposiums focused on the theme "Western Water Resources: Coming Problems and the Policy Alternatives."

In the years since that event, the demands on our water system have only increased and the challenges have become even greater. Today, anxieties are growing worldwide about the long-term trajectory of water availability, presenting global agriculture with a formidable long-term challenge. Recent and persistent extreme weather-related events have underscored the vulnerability.

The Federal Reserve Bank of Kansas City hosted a symposium titled "Agriculture's Water Economy" on July 11 and 12, 2016, to explore the dynamic link between agriculture and water, the role of markets and institutions, and the path forward. The ideas captured in the articles that follow were presented during the symposium. It is my hope that they will serve to inform those with an interest in the topic of water scarcity, its connection to agriculture, and the future of global food production.

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President and Chief Executive Officer
Federal Reserve Bank of Kansas City

Challenges and Policies for Global Water and Food Security

By Mark W. Rosegrant

Water is essential for growing food; for household uses including drinking, cooking, and sanitation; as a critical input into industry, for tourism and cultural purposes; and in sustaining the earth's ecosystems. But this essential resource is under threat. Growing water scarcity in much of the world poses challenges for national and subnational governments and for individual water users. The challenges of water scarcity are compounded by soil degradation in irrigated areas, the increasing costs of developing new water, overpumping and depletion of groundwater, water pollution and degradation of water-related ecosystems, and the wasteful use of already developed supplies encouraged by subsidies and distorted incentives that influence water use (Rosegrant).

Growing water scarcity and water quality constraints are a major challenge to future food security, especially since agriculture is expected to remain the largest user of freshwater resources in all regions of the world for the foreseeable future despite rapidly growing industrial and domestic demand. As non-agricultural demand for water increases, water will be increasingly transferred from irrigation to other uses in many regions. In addition, the reliability of the agricultural water supply will decline without significant improvements in water management

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policies and investments. The intensifying sectoral competition and water scarcity problems, along with the declining reliability of agricultural water supply, will put downward pressure on food supplies and continue to generate concerns for global food security.

Ringler and others project future water stress, showing that in 2010, 36 percent of the global population—approximately 2.4 billion people—live in water-scarce regions. In addition, 22 percent of the world's gross domestic product (GDP)—$9.4 trillion at 2000 prices—is produced in water-short areas (Figure 1). Moreover, 39 percent of global grain production is in water-stressed regions. In China, India, and many other rapidly developing countries, water scarcity has already started to materially risk growth—in these two countries alone, 1.4 billion people live in areas of high water stress today.

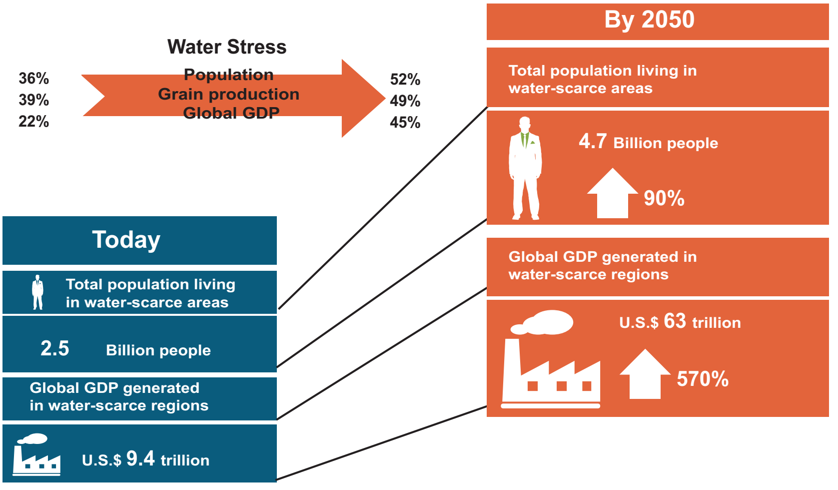
Business-as-usual (BAU) levels of water productivity under a medium economic growth scenario will not be sufficient to reduce risks and ensure sustainability. Under BAU, 52 percent of the global population (4.7 billion people), 49 percent of global grain production, and 45 percent ($63 trillion) of total GDP will be at risk due to water stress by 2050 (Figure 1). These risks will likely influence investment decisions, increase operation costs, and affect the agricultural competitiveness of certain regions (Ringler and others).

Section I summarizes projections for BAU outcomes for food security, showing that under the BAU scenario, increasing water scarcity and other factors are projected to slow agricultural growth and raise food prices. Section II provides evidence on the effect of water scarcity on economic growth, and Section III summarizes the relationship between climate change and water resources. Section IV deals with the policies, management, and technologies and investments that can lead to a better future for water and food security. Section V examines an alternative scenario to see whether plausible increases in water and crop productivity can provide significantly better outcomes for water and food security.

I. Water and Food Security

With declining water availability and limited land that can be profitably cultivated, expansion in area will contribute very little to future production growth. Slow growth in investment in agricultural research,

Figure 1
Projected Water Stress to 2050 under Business-as-Usual Scenario



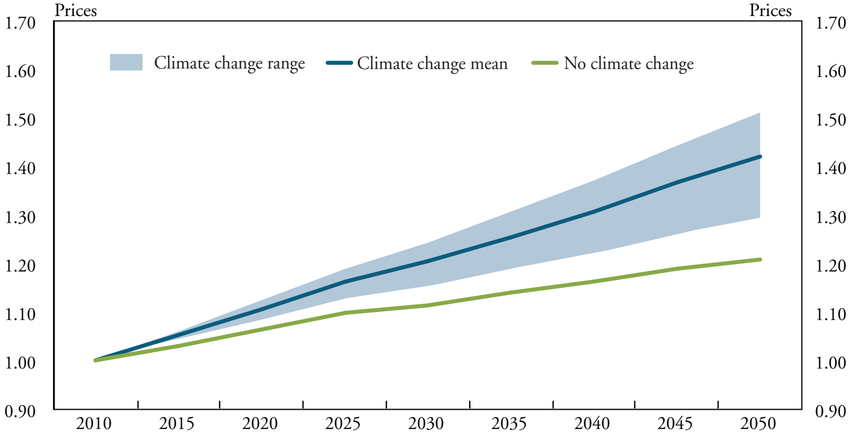
Source: Author based on Ringler and others.

irrigation, and rural infrastructure in developing countries is likely to dampen productivity growth; climate change will reduce the rate of productivity growth as well. These supply factors, coupled with growing population (mainly in Africa and South Asia) and rising income, are projected to raise food prices and slow improvements in food security under BAU conditions, as shown in Charts 1 and 2. International prices of grains are projected to increase by 20 percent even without climate change. With climate change, across a range of general circulation models, the mean price increase from 2010 to 2050 is projected to be approximately 50 percent. Meat prices are projected to increase by 20 percent as well, with a slight decline in prices after 2040 as developed countries, China, and Brazil reduce their per capita meat consumption (Chart 1).

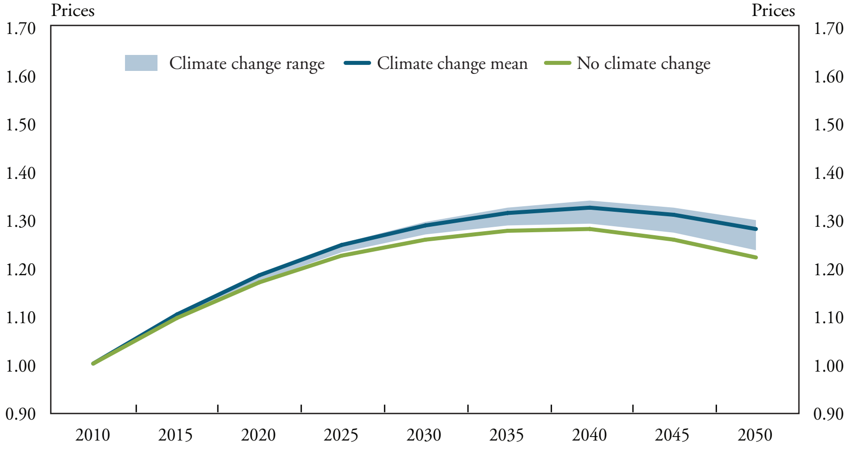
Other food prices are projected to increase in the range of 10–30 percent. These higher food prices also lead to slow reductions in hunger. Although Chart 2 shows projected reductions in the population at risk of hunger both with and without climate change, these reductions are far smaller than the targets in the United Nations Sustainable Development Goals, which call for ending hunger in 2030. With climate change, even by 2050, 155 million people are projected to be at risk of hunger in sub-Saharan Africa, 140 million in South Asia, and 530 million across the developing regions.

Chart 1
Projected Prices of Grains and Meats

Panel A: Grains

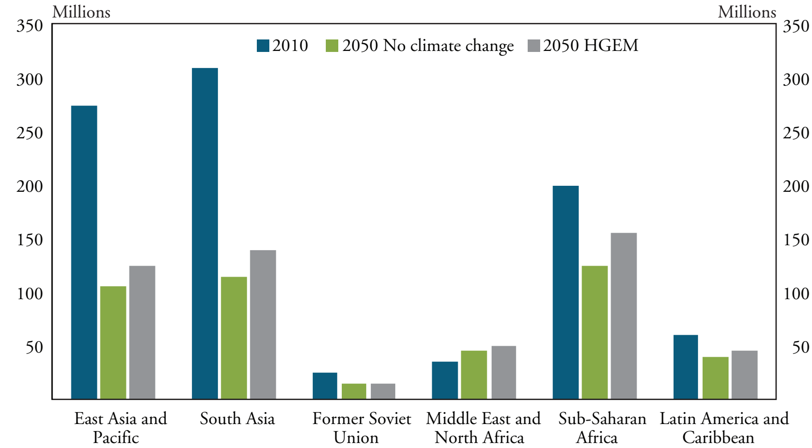


Panel B: Meats



Note: Real prices indexed to 2010 with and without climate change.
Source: Author from IMPACT results.

Chart 2
Projected Population at Risk of Hunger in 2050



Note: Chart shows projected population at risk of hunger in 2050 with and without climate change, using shared socioeconomic pathways 2 and representative concentration pathway 8.5.
Source: Author from IMPACT results.

II. Water and Economic Growth

In addition to their effects on agriculture and food security, water scarcity and water-related investments can increase economic productivity and growth. Sadoff and others summarize much of the evidence for this relationship. They conclude that the connection between water security and economic growth is intuitively clear, but that the empirical evidence of this relationship is scarce. More recent econometric analyses have considered variability in precipitation in addition to mean levels. Brown and others (2011), cited in Sadoff and others, show that rainfall variability, floods, and droughts have a statistically significant negative and detrimental effect on different measures of economic growth in sub-Saharan Africa. Brown and others (2013) find that anomalously low or high precipitation has a negative economic effect, thereby providing evidence that variability in precipitation can hinder growth.

Using an econometric model, Sadoff and others show that runoff has a statistically significant positive relationship with growth, indicating that greater water availability has a significant and positive causal effect on economic growth. Drought is shown to have a statistically significant negative effect on economic growth as well. On average, a major drought (affecting 50 percent or more of a country's area) is found to reduce economic growth (as measured by per capita GDP) by about half a percentage point in that year. Flood extent likewise has a negative effect on per capita GDP growth. Simulations that determine the benefits of reduced drought demonstrate that the effect of droughts may compound over a long time period. Sadoff and others also find that the effects of hydro-climatic variables on growth are strongest in poor countries and countries with high human water stress, high dependence on agriculture, or both.

The World Bank (2016) simulates the effect of water on economic growth using a Computable General Equilibrium (CGE) model that captures how changes in the water sector affect the rest of the economy. The economic consequences are highly unequal, with the worst effects in the driest regions. The expected global damage is small relative to expected global GDP in 2050. But global damage is a highly misleading estimate, because significant variations exist between regions. Western Europe and North America, where much global GDP is produced, experience negligible damage in most scenarios. The bulk of losses are in the Middle East, the Sahel, and Central and East Asia, and the magnitude of the losses is largely driven by the water deficit. Specifically, the GDP loss in 2050 under a water-constrained scenario amounts to −7 percent in East Asia, −7 percent in Central Africa, −11 percent in Central Asia, −11 percent in Sahel, and −14 percent in Middle East (World Bank 2016).

Economic feedback effects and adjustments can limit the damage from water shortfalls. Apart from the direct effect of water shortages on yields and crop areas, macroeconomic outcomes are similarly affected by prices and international trade. Liu and others, also using a CGE model, find that even countries experiencing negative output shocks due to reduced irrigation availability may gain from the higher commodity prices caused by the shocks. Regions can take advantage of trade to adjust the composition of agricultural income and specialize in more beneficial commodities. These adjustment effects, which are mediated by markets, reduce the initial effect of reduced water availability in farming.

III. Effects of Climate Change on Water

Climate change is projected to substantially change mean annual streamflows, the seasonal distributions of flows, the melting of snowpack, and the probability of extreme high- or low-flow conditions. The effects of climate change on water resources include changes in the timing of water availability due to changes in glaciers, snow, and rainfall; changes in water demands due to increased temperatures; changes in surface water availability and groundwater storage; an increased number and intensity of extreme climatic events (droughts and floods); changes in water quality; and sea-level rise (Rosegrant, Ringler, and Zhu). World Bank (2010) shows that most regions will experience more intense and variable precipitation, often with longer dry periods in between (Burke and Brown; Burke, Brown, and Christidis). The effects on human activity and natural systems will be widespread.

The ultimate outcome of climate change and its effects on water availability is difficult to project. Unknowns include geographic location, direction of change (less or more precipitation), degree of change in precipitation (low or high), change in precipitation intensity (low or high), and timing (within the next five years or over multiple decades). Shifting precipitation patterns and warming temperatures could increase water scarcity in some regions, while other areas may experience increased soil-moisture availability that could increase opportunities for agricultural production (Malcolm and others). But as the World Bank (2010) notes, these uncertain changes will certainly make it harder to manage the world's water. In addition, people will feel many of the effects of climate change through water. Climate change will make flexible water allocation more important to adjust to extreme events and changes in the timing of water availability, water demands, and surface water availability.

IV. Water Policies and Investments

Meeting the challenges of climate change and water availability will require action on many fronts. This section summarizes critical priorities to enhance water use efficiency and productivity.

Investing in crop breeding for yield per unit of water and land

The first step to better water use productivity is not directly part of the water sector: productivity gains for both irrigated and rainfed agriculture. Cai and Rosegrant find that while both increases in crop yield and improvements in basin efficiency contribute to increases in water productivity (crop yield per meter of applied water), the larger contribution comes from increases in the crop yield. Moreover, improvements in rainfed crop yield per hectare and unit of water would reduce pressure on irrigated crops. Plant breeding can improve plant biomass per unit of water through transpiration rates and can improve the efficiency of biomass growth per unit of transpiration. Although improvement in crop yield per unit of water use is a challenging breeding goal, it continues and has further potential (Richards and others 1993; Richards and others 2002; Ortiz and others). Diverse genes are essential for effective breeding for drought tolerance and other traits to get more yield per unit of water. To support a broad and targeted gene pool, the tools of biotechnology should be employed, including marker-assisted selection, cell and tissue culture, and gene editing, even if countries elect to forego transgenic breeding (Morison and others; Christensen and Feldmann).

Adopting new irrigation technologies and farming systems

Improved irrigation technologies, such as drip and sprinkler irrigation; and crop and water management, such as enhanced water harvesting, conservation tillage, and precision farming that optimizes application of water and other inputs within the field; can improve yields and enhance rural and farm incomes. However, because of the interconnected nature of water supplies, with runoff from one water user often being available to other users through return flows, different outcomes are possible when a new technology is put in place. For example, new technology can save water that would otherwise evaporate unproductively, providing net system benefits; divert water that would otherwise be used downstream by others, shifting benefits between farmers, rather than generating new benefits; or induce increased water use by increasing the profitability of irrigation for individual farmers rather than saving water (World Bank 2010). Farmers have many reasons to adopt advanced irrigation technologies, including increased income from higher value crops, convenience, labor-saving, and lower pumping costs; however, real water savings are more difficult to achieve and often limited (Perry and others).

The potential benefits of new technologies and farming systems are promoted by a water allocation system that recognizes these hydrological realities. Well-specified water rights and allocations have the potential to significantly improve water and food security and tap the potential gains of new technologies.

Establishing water rights and water trading

Water rights are the cornerstone of efficient and equitable water management. Secure and well-defined water rights provide incentives for investment in more efficient technology; making those water rights tradable provides additional incentives to optimize the economic value of water. Moreover, a properly managed system of tradable water rights provides incentives for water users to internalize the external costs imposed by their water use, reducing the pressure to degrade resources (Easter and Huang; Rosegrant and Binswanger). Young lays out a blueprint for establishing water rights and trading based in significant part on the experience in the Murray Darling River Basin in Australia. The conditions for effective water rights should include a perpetual right to a proportion (share) of all allocations made in the river basin or system. The actual allocation made in any season should be specified as a share of the total water available determined in a transparent process and accounting for system evaporative losses and environmental outcomes, including water quality and flows to the sea (Young; Young and McColl).

Establishing water rights that create incentives for efficient water use as well as trading systems to optimize economic returns has proven very difficult even in developed countries. In developing countries, the high costs of measuring and monitoring water use where infrastructure and institutions are weak and irrigation systems are often large and service many small farmers can also be a major constraint to implementing water rights and trading. Adding to the difficulty of reform, both long-standing practices and cultural and religious beliefs have treated water as a free good, and entrenched interests benefit from the existing system of subsidies and administered allocations of water (Rosegrant, Ringler, and Zhu 2009). Well-defined water rights and trading in developing countries would be enhanced by improved irrigation technology for conveyance, diversion, and metering; institutional improvement in the management of irrigation systems; and in many cases, community organizations to manage water allocation. Developing well-specified water rights and trading is likely to be a medium- to long-term process in most developing countries. An initial focus on realistic allocation of water on a seasonal basis—along with registration of rights based on shares—would be a major first step.

Groundwater use in much of the world has increased very rapidly in a short period of time, particularly in Asia, where cheap pumps are available and energy and water are often subsidized. While expanding groundwater use has been highly beneficial, overdrafting is excessive in many instances, causing land subsidence, salinization, and other degradation of land and water quality in the aquifer. The principles of groundwater management through water rights and trading are essentially the same as described above, but are even more complex than surface systems due to the invisibility of the resource, the lack of data on safe yield or availability, and groundwater movement. Elements of successful groundwater management include recognized user rights, monitoring processes, means for sanctioning violations, and procedures for adapting to changing conditions. Again, institutional capabilities to establish such systems are lacking in most developing countries, but measuring groundwater and establishing clear rights would be an important step forward.

Capital investment in irrigation and water

Because new investments in irrigation and water supply are increasingly expensive and politically sensitive, hard infrastructure investment has a reduced role globally compared with past decades, when dam-building and expansion of irrigated area drove rapid increases in irrigated area and crop yields, particularly in developing countries (Rosegrant, Ringler, and Zhu). Still, some regions of the world have substantial potential for irrigation expansion. The World Bank's Africa Infrastructure Country Diagnostic (AICD) study concludes that Africa has the potential to add at least 16 million hectares of profitable large-scale irrigation (You and others). Xie and others show an even greater potential for profitable smallholder irrigation expansion in sub-Saharan Africa: the authors identify area expansion potential up to 30 million hectares for motor pumps, 24 million hectares for treadle pumps, 22 million hectares for small reservoirs, and 20 million hectares for communal river diversions. The technologies can benefit between 113 million and 369 million rural people in the region, generating net revenues of $14–22 billion depending on technology.

Finally, large additional investments in water treatment and sewage disposal plants will be required. Various estimates exist for the necessary investments to improve sanitation standards, especially in the developing world. In a study commissioned by the World Health Organization, Hutton and Haller estimate that access to improved water and sanitation services for all would cost around $22.6 billion per year, and access to both regulated, in-house piped water supply with quality monitoring and in-house sewerage connection with partial treatment of sewage would require a total investment of $136.5 billion per year.

V. The Effects of Improved Water Use Efficiency and Productivity

Can implementing the measures described above significantly improve water and food security compared with the outcomes in the BAU scenario? Rosegrant and others (2013) simulate an alternative scenario for water and food security that combines water use efficiencies in the domestic, industrial, and irrigation sectors to reflect direct water-saving effects, higher crop productivity growth per unit of water consumed, and the resultant higher GDP growth stimulated by higher agricultural productivity. The authors use the International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT): a partial equilibrium, multicommodity, multicountry model that generates projections of global food supply, demand, trade, and prices as well as water supply and demand (see Rosegrant and others 2012 for a detailed description of IMPACT). The CGE model GTEM is used iteratively with the IMPACT to generate the multiplier effects from agricultural and water sector productivity growth to GDP growth (Ahammad and Mi). The efficiency gains for industrial and residential water use are taken from the WaterGAP model (Ozkaynak and others). The underlying drivers for water use efficiency gains, as described in the Global Environment Outlook V (GEO5) report, include stringent efficiency measures taken in industry and residential water use. They also include climate policies that lead to reduced demand for thermal cooling in power generation, as fossil-fuel-powered plants are partly replaced by renewable energy sources. For agriculture, Rosegrant and others (2013) estimate the basin water use efficiency gains based on more efficient transpiration (including drought resistant varieties and other advances in research as described above), reduced non-beneficial evapotranspiration (ET), and reduced losses to water sinks (for example, due to water-conserving irrigation and crop management technologies and reduced evaporative losses during conveyance). The average efficiency gains for global, basin-level water use are 8.8 percent by 2030 and 14.5 percent by 2050 compared with the BAU scenario (Rosegrant and others 2013).

The simulated improvements in efficiency result in an improvement in irrigation water supply reliability (IWSR), defined as the annual ratio of irrigation water supply to demand. The degree of improvement varies by country and regions, but globally, IWSR is 0.619 under the BAU scenario and 0.726 under the higher efficiency and productivity scenario. This improvement results in higher reliability than in the 2000 base year while accommodating significant increases in irrigated area (Rosegrant and others 2013).

With higher crop yield growth and larger crop production under the more efficient scenario, prices for most crops, including rice, wheat, maize, and oils decline relative to the BAU scenario despite the higher income growth generated under the more productive scenario. Price declines are generally in the range of 10–20 percent in 2050 compared with the baseline. Prices for meat, fruits, and vegetables increase slightly, reflecting the effect of higher income on these commodity markets. Per capita food demand increases as a result of higher income growth and lower agricultural commodity prices.

Rosegrant and others (2013) also project the number of people facing the risk of hunger in the different regions of the world. With higher water and productivity growth expanding the food supply and pushing down food prices, and with improving GDP growth to boost per capita food consumption, fewer people will be at risk of hunger. In the projected alternative scenario, the number of people at risk of hunger declines significantly for all developing regions. The two regions with the most severe hunger issues gain the most sub-Saharan Africa has the biggest percentage drop in hunger, with a 44 percent reduction in the population at risk of hunger in 2050 compared with BAU, reducing the number of hungry people by 66 million in 2050 relative to BAU.

VI. Conclusions

Water scarcity is projected to increase in much of the world, and together with climate change and other factors will likely slow growth in agricultural productivity and slow progress in the reduction of hunger. But a plausible scenario for water and crop productivity growth—predicated on a set of water allocation reforms, new water technologies and farming systems, investment in crop research to increase yield with respect to water, and selective new investment in irrigation and water sanitation and sewage—can significantly improve water and food security outcomes. The precise mix of water policy and management reform and investments—and the feasible institutional arrangements and policy instruments used to achieve them—must be tailored to specific countries and basins and will vary across underlying conditions and regions, including levels of development, agroclimatic conditions, relative water scarcity, level of agricultural intensification, and degree of competition for water. These solutions are not easy, and they will take time, political commitment, and money.

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Long-Term Trajectories: Crop Yields, Farmland, and Irrigated Agriculture

By Kenneth G. Cassman

The specter of global food insecurity, in terms of capacity to meet food demand, will not be limited by water or even climate change but rather by inadequate and misdirected investments in research and development to support the required increases in crop yields. The magnitude of this food security challenge is further augmented by the need to concomitantly accelerate the growth rate in crop yields well above historical rates of the past 50 years during the so-called green revolution, and at the same time, substantially reduce negative environmental effects from modern, science-based, high-yield agriculture.

While this perspective may seem pessimistic, it also points the way toward solutions that lead to sustainable food and environmental security. Identifying the most promising solutions requires a robust assessment of crop yield trajectories, food production capacity at local to global scales, the role of irrigated agriculture, and water use efficiency.

I. Magnitude of the Challenge

Much has been written about food demand in coming decades: many authors project increases in demand of 50 to 100 percent by 2050 for major food crops (for example, Bruinsma; Tilman and others). The preferred scenario to meet this demand would require minimal conversion of natural ecosystems to farmland, which avoids both loss of natural

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habitat for wildlife and biodiversity and large quantities of greenhouse gas emissions associated with land clearing (Royal Society of London; Burney and others; Vermuelen and others). While efforts to reduce food waste and meat consumption can modestly decrease future demand for crop commodities, progress on those fronts requires significant modification of human behavior and reorganization of food systems that remain to be seen. Therefore, the prudent target for policymakers responsible for food security is to ensure crop yields increase at a rate that would meet the projected increase in food demand on the current agricultural land base, which for food crops is about 1.5 billion hectares.

The goal of meeting food demand on existing farmland, however, does not mean that no non-agricultural land will need to be converted to crop production due to urban sprawl. Seto and others project a global urban expansion of 130 million hectares by 2030. Because most cities are located in areas surrounded by farmland, meeting food demand in 2050 would therefore require converting upward of 100 million hectares of non-agricultural land to crop production.

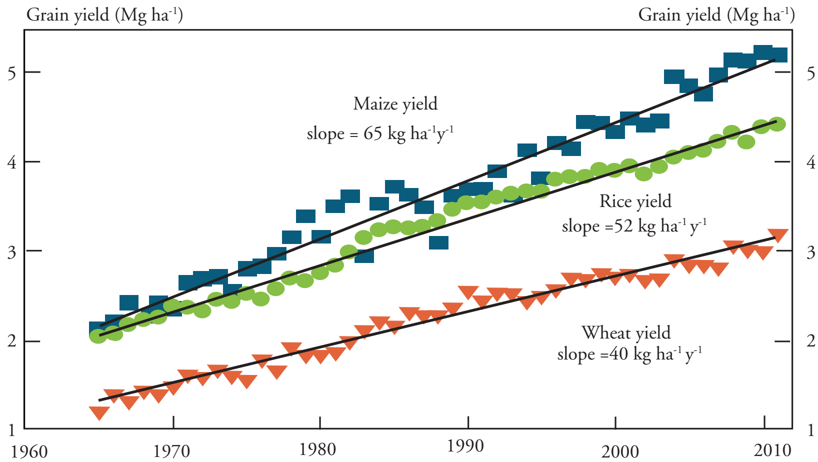
In addition to producing sufficient quantities of food to meet demand, production systems must also greatly reduce current negative effects on the environment and human health (for example, Horrigan and others) and alleviate pressure on natural resources (Green and others; Scanlon and others; Lawrence and others). Intensive, high-yield systems that account for the majority of global crop production require large external subsidies of energy, water, nutrients, and pesticides. In general, the efficiency with which these inputs are used to produce food is relatively low; greater efficiency could reduce negative environmental effects if such reductions can be achieved while also supporting continued growth in yields.

Hence the grand challenge is achieving a 50–100 percent yield increase on the existing area of cropland while also making substantial improvements in the efficiency with which inputs are used—a process called ecological intensification (Cassman). The remainder of this paper evaluates several key components of this challenge.

II. Are Current Yield Growth Rates Fast Enough?

Achieving a 50 to 100 percent increase in crop yields by 2050 requires 1.2 to 2.0 percent annual exponential yield growth rates.

Chart 1
Global Yield Trends of the Major Cereal Crops



Source: FAOSTAT.

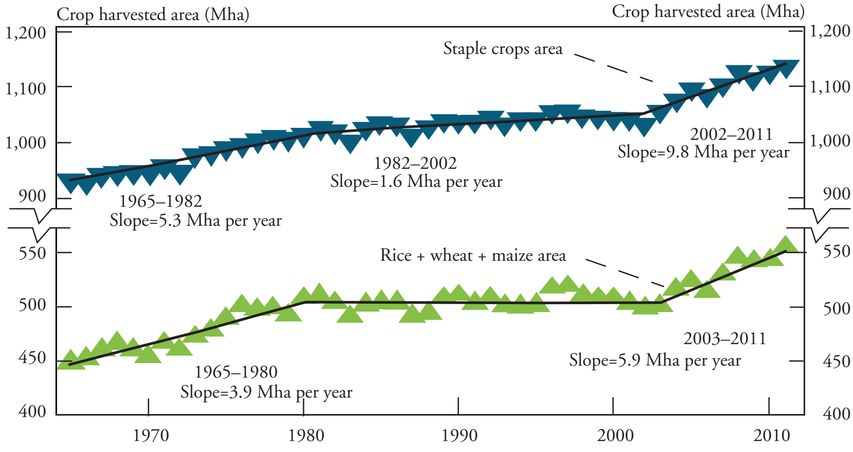
However, aggregate global rates of yield growth for major food crops have followed a decidedly linear path for the past 60 years: relative rates of gain (the ratio of the linear rate of increase to the yield in a given year) fell from 2.5 to 3.0 percent in 1965 to 1.2 to 1.3 percent in 2011 (Chart 1). If current linear trajectories are maintained, relative rates of gain will fall below 1.2 percent by 2020 for all three major cereal crops—maize, rice, and wheat—which means current rates of increase are much slower than required to meet projected demand by 2050. Instead, rates of gain must accelerate well above their trajectories of the past 50 years if food demand can be met without massive expansion of global crop area.

Evaluations of aggregate global yield trends mask important differences among countries. Using a robust spline regression approach, Grassini and others recently documented that yield growth rates of major cereals have stagnated or declined significantly in countries that account for 31 percent of total production. Stagnant yields are evident for rice in China, Korea, and California, and for wheat in most of western and northern Europe and India. The cause of this stagnation—and whether yield trends in other major crop producing countries will follow suit—is less clear.

Because yield growth is not keeping pace with food demand, there is increasing pressure to expand crop production area. In fact, harvested

Chart 2

Trends in Global Harvested Area, 1965–2011



Source: Grassini and others.

crop area has been increasing at an annual rate of 10 million hectares (Mha) since 2002, which is faster than at any time in human history (Chart 2)for the 10 major staple food crops. About 60 percent of this increase is due to increased production area of maize, rice, and wheat. When soybean, oil palm and sugarcane are also considered (data not shown), these six crops account for about 85 percent of the total increase. Unless rate of growth in crop yields accelerates well above historical trajectories shown in Chart 1, large-scale conversion of land to crop production will likely continue.

III. Biophysical Yield Limits and Farm Yield Trajectories

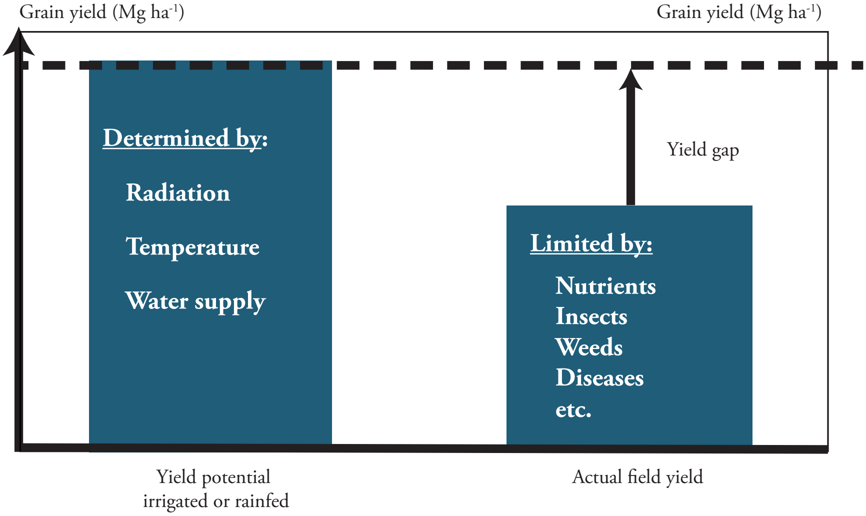
Several factors can contribute to stagnating yields or even yield decreases. One such factor is political disruption, as occurred in Russia and several central Asian countries for several years after dissolution of the Soviet Union in 1989. Stagnation can also result from economic turmoil or poor agricultural policies that restrict affordability and access to production inputs or that decrease prices farmers can expect for their crops. Strict regulation of input use, such as nitrogen (N) fertilizer or transgenic crops (also called "genetically modified crops" or GMOs) could also reduce the rate of yield gain.[1] In addition, climate change and associated temperature increases may negatively affect yields, though to date, a clear signal of these negative effects is muted because the magnitude of the temperature rise is not large and farmers can adjust management practices to both attenuate negative effects and take advantage of opportunities warmer temperatures present. Examples of opportunistic farming with warmer temperatures include earlier planting with longer-maturing cultivars and planting two crops per year where only one was planted previously.

Another reason for yield stagnation is that average farm yields have approached the biophysical yield ceiling determined by climate and rainfall—factors not modified by management. For irrigated crops with adequate water to avoid deficits, the biophysical yield ceiling is called yield potential (Yp) and is governed by temperature regime, which determines the length of the growing season, and the amount of solar radiation during the growing season. For non-irrigated crops, hearafter called rainfed crops, potential yields (Yw) are water-limited and thus additionally depend on the quantity and timing of rainfall and the capacity of soil to store it. The yield gap is the difference between Yp or Yw and actual field yield (Figure 1).

For a given length of growing season, both Yp and Yw are largely determined by rates of photosynthesis and respiration, which together govern biomass accumulation. The leaf photosynthetic rate is governed by temperature, solar radiation, and plant water and nutrient status. Although there has been tremendous genetic improvement against yield-reducing factors through greater insect and disease resistance and herbicide resistance to improve weed control, there has been relatively little improvement in maximum rates of photosynthesis or in respiration efficiency to support maintenance and growth (Hall and Richards). As a result, Yp and Yw of maize and rice have remained little changed over the past 50 years (Duvick and Cassman; Peng and others) while the genetic yield ceiling of wheat has improved modestly (Cassman).[2]

At the field level, farmers can sometimes increase Yp or Yw by lengthening the growing season through earlier planting or use of a later-maturing cultivar. All else equal, this tactic increases the yield ceiling by prolonging the period for capture of sunlight and conversion to biomass. But a longer growth period carries risks: a greater chance of damaging weather events (wind and hail storms, early frost) and, in temperate climates, greater costs for grain drying. Achieving earlier leaf canopy closure by raising seeding rates can also give higher yields

Figure 1
Yield Potential, Yield Gaps, and Their Determining Factors

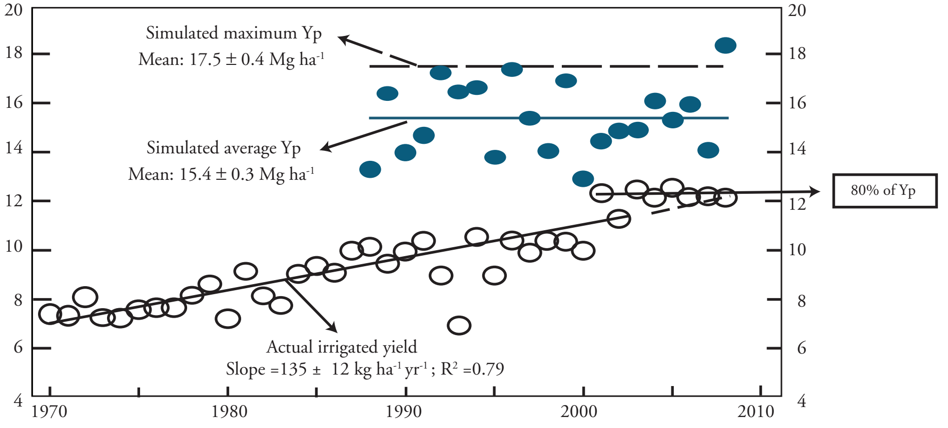


in some cases, though high seed costs and a greater risk of lodging and disease in dense plant stands give diminishing returns.

Indeed, farmers do not strive to achieve maximum yields and instead try to maximize profit. Maximum profit is obtained at a yield level below Yp or Yw due to the diminishing returns from additional inputs such as fertilizer, water, seed, labor, and pest control measures as yields rise toward the yield ceiling. Therefore, average yields begin to plateau for a population of farmers when their average yield reaches 75 to 90 percent of the Yp or Yw yield ceiling (Cassman; Cassman and others). The relative yield at which stagnation occurs reflects the risks associated with obtaining a return on investment from additional inputs and the price ratio of inputs versus grain (Lobell and others).

The hypothesis that farm yields stagnate as they approach Yp or Yw can be tested by estimating ceiling yields with a robust crop simulation model and actual weather and soil data. Using this approach for irrigated rice in China suggests yield stagnation occurs at 82 percent of Yp, whereas yield stagnation of wheat in Germany occurs at 80 percent of Yw (Van Wart and others). For irrigated maize in central Nebraska, stagnation is beginning to appear at 80 percent of Yp (Chart 3). In that study, a Yp of 15.4 megagrams per hectare (Mg/ha)—equivalent to 15.4 metric tonnes per hectare, or about 250 bushels per acre—is

Chart 3
Yield Trends of Irrigated Maize in Nebraska



Notes: Irrigated maize yields achieved by farmers in central Nebraska (open circles) with yield potential (Yp) estimated in two ways, both based on actual weather data for each year: (1) with current management practices used by farmers for sowing date, seeding rate, and hybrid maturity (closed circles and line), and (2) optimal management to maximize yields as discussed in the text (dashed line). Suggested yield stagnation since 2001 occurs at a yield that is 80 percent of yield potential with current management.
Source: Grassini and others (2011a).

estimated based on current management used by farmers in terms of sowing date, seeding rate, and hybrid maturity. Modified management that includes earlier sowing, higher seeding rate, and a later maturing hybrid could increase Yp by 14 percent to 17.4 Mg/ha. But there is little barrier to adoption of these options, which means that Nebraska farmers choose not to adopt such practices, most likely due to higher costs of seed and grain drying, and nearly doubling the risk of early frost during grainfilling (Grassini and others 2011a). These findings are consistent with the proposition that farmers strive to maximize profits with an acceptable level of risk and do not seek to maximize yield.

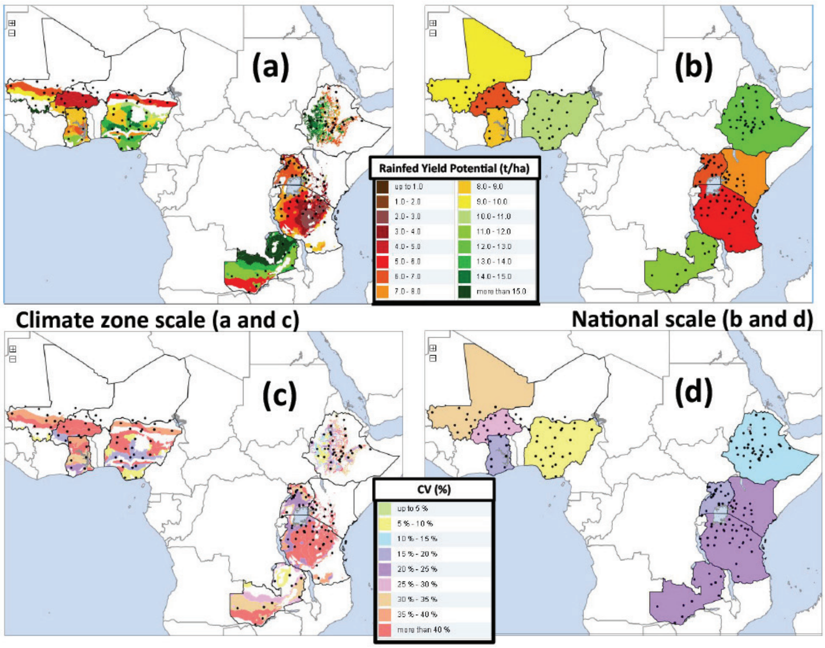
IV. Estimating Food Production Capacity at Local to Global Scales

Recent advances in computing power, crop simulation models, and spatial analysis—coupled with steady improvements in availability and access to spatially explicit databases on climate, soils, and crop area extent—now make it possible to estimate crop production capacity on every hectare of existing farmland. To this end, the *Global Yield Gap and Water Productivity Atlas* has completed detailed yield gap assessments of major crops in 30 countries with aspiration for complete global coverage. In contrast to previous assessments that use relatively coarse spatial data for current and potential yields, soils, and climate with a "top-down" scaling approach (such as Licker and others; Mueller and others), the *Global Yield Gap and Water Productivity Atlas* relies on local primary data to the extent possible coupled with a robust "bottom-up" scaling technique that provides yield gap estimates at local to global levels (Grassini and others 2015; van Bussel and others). Use of long-term weather data at specific locations selected for their representation of large crop production areas and well-validated crop simulation models provide estimates of both potential yields and yield stability (Map 1). All of the analyses and most underpinning data are available for download from the Atlas website.

Recalling that the yield gap (Yg) is calculated as the difference between irrigated (Yp) or rainfed (Yw) yield potential and actual yield, estimating Yg for a given country provides information about its capacity to meet future national food demand from existing farmland, assuming farmers can achieve a yield that is 80 percent of yield potential. Such analyses are essential for strategic planning about future food security. Some countries may find they cannot produce sufficient quantities of staple crops on existing farmland and then make plans to ensure adequate, reliable, and affordable supplies. Options include expanding production area, imports, or both. The reliability of the food supply is especially important for low-income, food-deficit countries, as seen during the global 2008 food crisis. Estimates of yield instability (see the coefficient of variation in Map 1) provide a quantitative estimate of supply reliability of national or regional production.

In some cases, a country or a region (such as West Africa) may have sufficient production capacity to meet projected demand on existing rainfed farmland or by expanding production area, but the reliability of that supply may be erratic due to highly variable rainfall. Indeed, most of sub-Saharan Africa (SSA) relies heavily on rainfed crop production because only 4 percent of its current crop area is irrigated. Despite relatively high annual rainfall in much of SSA cereal areas, Yg analyses from the Atlas identify yield stability as a major problem: the coefficient of variation in cereal Yw is similar to that in the westernmost U.S. Corn Belt, where temporal yield variability is also high (Chart 4). Low

Map 1
Screenshots from the *Global Yield Gap and Water Productivity Atlas*



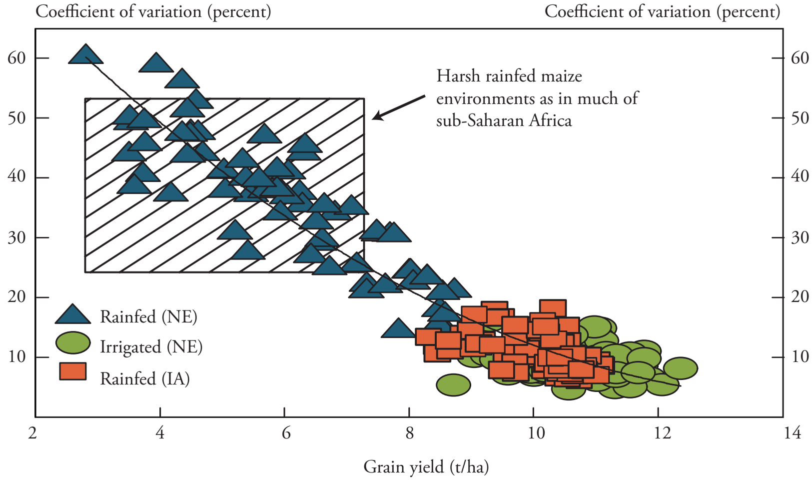
Note: Screenshots A and B show rainfed maize yield potential. Screenshots C and D show the coefficient of variation due to yearly variation in weather shown as a percentage of yield potential. Data are mapped at two spatial scales: climate zones (A and C) and country (B and D). The data are also available from the *Global Yield Gap and Water Productivity Atlas* website at the local scale of individual weather stations shown as black dots located in regions with the greatest crop production area.
Source: *Global Yield Gap and Water Productivity Atlas*.

stability in SSA cereal yields despite generous rainfall reflects warmer temperatures, greater transpiration demand, and shallower soils than in the U.S. Corn Belt. Expanding irrigation would help stabilize national and regional production if sustainable water resources were available to support it. Two recent reports suggest that food security in SSA is likely to depend in part on the expansion of irrigated farmland (You and others; Cassman and Grassini). Moreover, hydrological evaluations indicate adequate ground and surface water resources to support substantial expansion in irrigated farmland in some regions of SSA (for example, MacDonald and others).

Yield gap assessments identify other countries with production capacity for one or more staple food crops that exceed projections of future demand based on population and income growth. These countries can consider

Chart 4

Relationship between Yield Instability and Grain Yield



Notes: Chart shows relationship between yield instability (quantified by the coefficient of variation in yield) and average grain yield (2001–10) from maize-producing counties in Iowa and Nebraska. A rainfall gradient from western Nebraska (low and highly variable rainfall) to eastern Iowa (high and reliable rainfall) accounts for the observed range in yield and yield stability for rainfed crops. Analysis from the Global Yield Gap and Water Productivity Atlas- documents that much of rainfed maize production in West and East sub-Saharan Africa have average yields and yield instability within the dashed box.

leveraging that capacity through investments in infrastructure and education to support increased production and to remain competitive in global markets. Argentina, for example, has substantial capacity for increased crop production on existing rainfed farmland—in fact, a recent yield gap analysis by Merlosa and others found current farm yields to be 59 to 68 percent of Yw (Table 1). By raising average yields to 80 percent of Yw, Argentine farmers could produce an additional 7.4, 5.2, and 9.2 million metric tonnes (Mt) of soybean, wheat, and maize on the existing crop area, representing 9 percent, 4 percent, and 9 percent, respectively, of current global exports of these commodities.

V. Irrigated Agriculture and Food Security

On a global scale, irrigated agriculture supplies about 40 percent of our human food supply on less than 20 percent of farmland (FAO). In addition to the quantity of food produced, irrigated agriculture provides “ballast” to local, regional, and global food supply in several ways. First, irrigated cropland is much higher yielding than rainfed cropland, especially in semiarid and subhumid climates. For example, in

Table 1
Current and Potential Crop Production in Argentina

Crop	Current yield (tonnes per hectare)	Yield potential (tonnes per hectare)	Yield gap (tonnes per hectare)	Current yield as percent of yield potential	Crop area (million hectares)	National production capacity (million tonnes)
Soybean	2.7	3.9	1.2	68	17.6	55
Wheat	3.0	5.2	2.2	59	4.5	19
Maize	6.8	11.6	4.8	59	3.7	34

Note: Production capacity is estimated at 80 percent of yield potential.
Source: Merlosa and others.

central and western Nebraska, where both irrigated and rainfed maize are produced, irrigated maize yields currently average about 12 tonnes per hectare, which is nearly double or triple the yields from rainfed maize. Second, yield stability is substantially greater in irrigated systems. The coefficient of variation for rainfed maize in central and western Nebraska ranges from 30–60 percent, which is four to eight times greater than the coefficient for irrigated maize in the same region (Chart 4). Third, high and reliable yields from irrigated systems attract supporting investments in local infrastructure, agricultural equipment manufacturing, seed and input suppliers, crop consultants, and value-added enterprises such as food processing, livestock feeding operations, and slaughterhouses. It is worth noting that in 1819, Major Stephen Long was sent by President James Monroe to explore the Louisiana Purchase along the Platte River watershed in central and western Nebraska. In his reports, Major Long famously described the area as a "Great American Desert." Today, because of its irrigated agriculture and associated livestock and biofuel industries, Nebraska has the highest per capita agricultural gross domestic product of any state in the nation.

VI. Is Irrigated Agriculture Sustainable?

High yields from irrigated crop production reduce pressure to expand crop area. Nonetheless, as irrigated agriculture appropriates a large portion of global fresh water withdrawals, many believe that irrigated agriculture is not sustainable. However, food prices would rise dramatically if irrigated agriculture were greatly scaled back, and meeting projected food demand without irrigated agriculture is simply not feasible. Hence, the long-term viability of irrigated agriculture and its future contribution to food security will depend on the answers to two questions. First, is it possible to maintain the current area of irrigated production while also accommodating other demands on surface water supplies and maintaining aquifers without overdrafting? And second, how much can increased water use efficiency contribute to expanding irrigated production area without increasing or in some cases decreasing, total water withdrawals?

Future trends in irrigated crop area

A comprehensive evaluation of global water supplies for irrigated agriculture is beyond the scope of this paper. But there is clear evidence and widespread agreement that most of the world's major aquifers and river basins are currently overappropriated by a large margin (Wada and others; Hoekstra and others). Coupled with concerns about water scarcity and the negative environmental effects of reduced stream and river flow from water diversion for irrigation, a significant increase in irrigated area is unlikely (Scanlon and others; Pfister and others; Rosegrant and others). Instead, expansion in some regions may offset reduction in others where overdrafting and competition with non-agricultural uses are prominent. As previously mentioned, SSA has substantial potential to increase the irrigated area. And recent experiences with irrigated agriculture in California, Nebraska, and Texas provide important insights into future global trends.

California's Central Valley is a region with intense competition for water between agriculture and other sectors, and total irrigated area has been in decline (Table 2). Aquifers are overdrafted, and environmental regulations and extended drought have reduced water supplies for irrigation (Scanlon and others). In 2015, the fourth consecutive year of severe drought, about 7 percent of irrigated land was fallowed due to restricted water supply. Additional areas received substantially less water than normally allocated. In response, California's farmers focused limited water supplies on the highest value crops and invested in new wells and technologies to increase irrigation efficiency. The result was a relatively small reduction in yields and a decrease in total crop value of less than 3 percent (Howitt and others). With normal rainfall in 2016, most major

Table 2
Changes in Irrigated Crop Area, 1997–2012

State	Irrigated crop area (million hectares)	
	1997	2012
California	3.60	3.18
Nebraska	2.84	3.36
Texas	2.33	1.82

Source: USDA.

reservoirs in California have sufficient storage to meet normal irrigation water commitments, though it will take many more years of above-average rainfall to replenish aquifers that were heavily overdrawn.

In contrast to California, irrigated area in Nebraska continues to increase, and Nebraska now has more irrigated crop area than any other state (Table 2). This increase has occurred without overdrafting the northern High Plains Aquifer that sits under much of Nebraska (Scanlon and others). The High Plains Aquifer is the state's primary water supply for irrigated cropland. Proactive policies and a robust regulatory framework, as applied by the state's Natural Resource Districts (NRDs), are in large part responsible for this outcome. Each of the 23 NRDs represents a watershed or part of a watershed, and they have both taxing and regulatory authority to implement state laws governing conjunctive use of surface and groundwater and to implement federal and state laws governing water quality (Bleed and Hoffman). When aquifer levels fall below predetermined thresholds, NRDs have the authority to regulate water use accordingly until aquifer withdrawals and recharge return to balance. The success of this approach can be seen in well monitoring data over many decades, which document no depletion in all but a few areas. Water use in those few areas remains under tight regulation until water resources are in compliance. In contrast, the water level in the southern High Plains Aquifer under Texas has seen substantial decline (Scanlon and others), and irrigated area in that state has decreased by 22 percent between 1997 and 2012 (Table 2). Unlike Nebraska, policies and regulations regarding use of groundwater are not under a system of local control and have not been as rigorous in avoiding overappropriation.

Opportunities to improve irrigation water use efficiency

In a world with rising competition for water resources, achieving greater water use efficiency is necessary, but not sufficient, to support the long-term viability of irrigated agriculture. Effective policies and regulations are also required to ensure water resources are not overappropriated. Assuming effective regulations are in place, improving the efficiency with which irrigation water is converted to economic yield is a powerful tool to maximize productivity of a limited water supply.

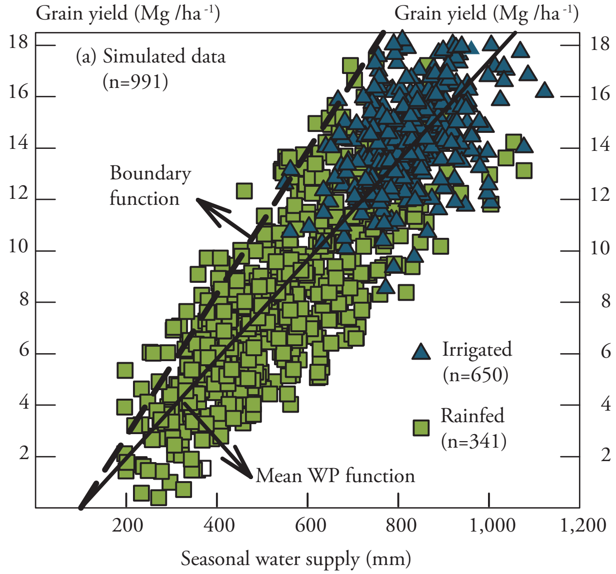
In general, however, irrigation is relatively inefficient worldwide because both water and energy were inexpensive during the 1950–90 period when most large-scale irrigation systems were designed and developed. Typical irrigation systems installed during that period relied on surface irrigation, which is the most inefficient method of water application due to difficulties in achieving uniform water distribution. The rise in energy prices since the 1990s and development of pivot and drip irrigation systems provided both incentive and opportunities for substantial efficiency improvements.

For a given crop, water productivity (WP) is a useful metric for evaluating water use efficiency of both irrigated and rainfed crop production. WP is calculated as the ratio of economic yield to total water supply. Total water supply includes stored soil moisture at time of sowing of annual crops or the beginning of the growing season in perennial crops, rainfall during the crop growth period, and applied irrigation. For a given crop species, there are robust, generic WP benchmarks that relate yield to total water supply under optimal growth conditions for all factors other than temperature and solar radiation in irrigated production, and for all factors other than temperature, solar radiation, and rainfall in rainfed production (Chart 5, Panel A). Whereas the WP *frontier boundary* represents the maximum WP that maize can achieve in years with the most favorable weather for crop production, the *mean WP function* represents the average WP expected across year-to-year variations in weather (Grassini and others 2011a). Under irrigated production, variation in WP due to weather is caused by differences in temperature and solar radiation during the growing season. For example, in a year with a short-term spike in temperature above 35° Celsius (95° Fahrenheit) in the critical three-day pollination period, the number of grains per ear will be reduced, leading to below-average yields even though

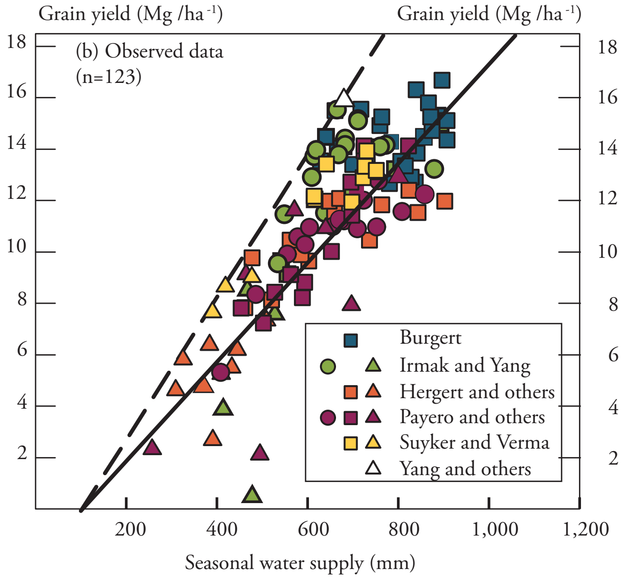
Chart 5

Relationship between Grain Yield and Water Supply

Panel A: Simulated



Panel B: Actual



Notes: Panel A shows the relationship between simulated maize grain yield and seasonal water supply (available soil water at sowing to 1.5m depth, plus sowing-to-maturity rainfall and applied irrigation), modified from Grassini and others (2009b) as simulated over a 20-year period at 18 sites across the U.S. Corn Belt. Dashed and solid lines are the boundary and mean WP functions, respectively (slopes = 27.7±1.8 and 19.3±0.4 kg ha–1 mm–1, respectively; x-intercept = 100 mm). Panel B shows actual grain yield and water supply data from field studies in the western U.S. Corn Belt that are managed to produce yields without limitation from nutrients or pests under rainfed (■), irrigated-sprinkler or pivot (▲) or subsurface drip irrigation (●).
Source: Grassini and others 2011b.

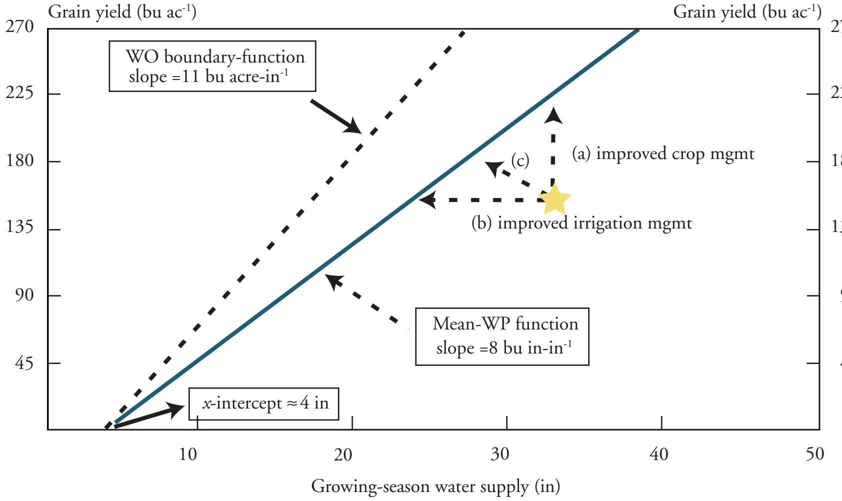
season-long water requirements may be average: this gives WP below the mean WP function line. Likewise, a year with cool night temperatures and warm sunny days during grainfilling results in a larger seed size and above-average yields, which gives WP above the mean WP function line. Under rainfed production, observed variation in WP is mostly due to variation in rainfall distribution during the growing season and, in particular, rainfall deficits during sensitive reproductive growth stages such as early seed differentiation, pollination, and grainfilling.

The most appropriate WP benchmark for a population of farmers is the mean WP function line as shown in Panel A of Chart 5 for two reasons. First, this function accounts for expected variation in weather. Second, it has been rigorously validated across a wide range of environments in carefully managed field studies that utilize agronomic management practices that explicitly seek to minimize yield loss from all production factors other than water supply (Chart 5, Panel B).

The WP framework can be used to evaluate the WP of an individual field (Chart 6) or a population of farmer's fields in a watershed or region. In both cases, performance can be compared with the benchmark functions to determine the potential for increasing WP. Options for an individual field, for example, can be evaluated in terms of increasing WP by raising yields through use of improved agronomic practices. In this case, WP increases because of higher yields without a change in water supply. Likewise, WP can be improved with higher water use efficiency—for example, through modifications that improve irrigation timing, amount, and application method (such as pivot versus surface irrigation). In most cases, the most cost-effective option for obtaining higher WP involves improvements to both agronomic management and irrigation method. This evaluation is robust because it requires only yield and irrigation water application amount data from farmers; data on stored soil moisture at planting and rainfall can be obtained from several nearby weather stations for each field (Grassini and others 2011a, b).

Evaluating farmer-reported data on maize yields and irrigation water application over a three-year period in the Tri-Basin NRD in central Nebraska provides an example of WP performance for a population of farmers in a watershed (Chart 7). In the Tri-Basin NRD, farmers are required to install a high-quality flow meter on all irrigation wells and

Chart 6
Water Productivity of an Individual Field versus Benchmarks



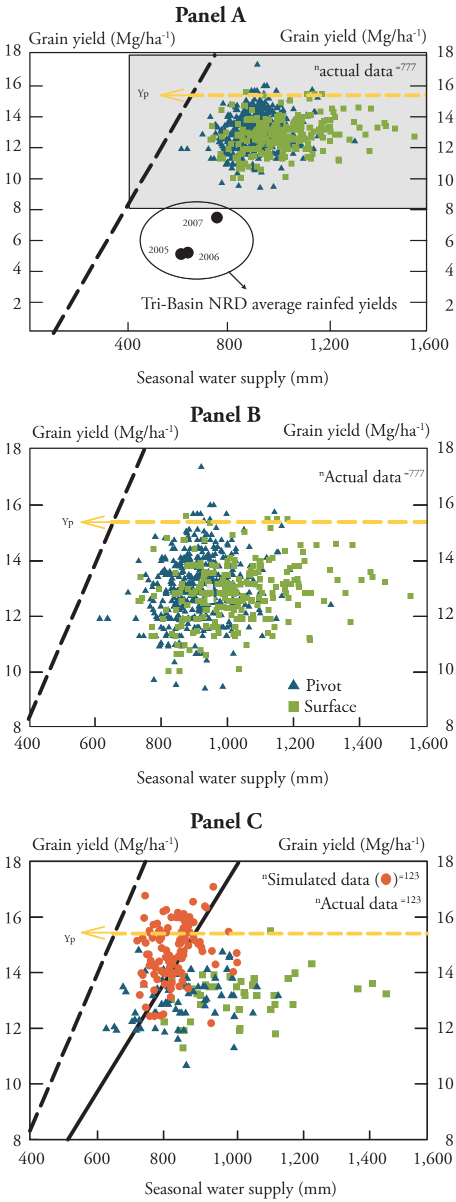
Notes: Chart shows performance of an individual farmer's field (★) relative to WP benchmark functions and options for increasing WP by better management to give higher yields with the same total water supply through improved agronomic practices (arrow a, including choice of cultivar, sowing date, stand establishment, and reduced yield loss from insects, disease, weeds, and nutrient deficiencies), improved irrigation efficiency (arrow b), or both (arrow c). WP benchmarks here are the same as in Chart 5, converted to English units for yield (bushels per acre) and water (depth in inches).

to report both irrigation water use and yield on an annual basis. The NRD uses this information to inform compliance options. Evaluating these data provides quantitative insight into factors governing WP and the most cost-effective options to improve it. When combined with additional farmer-reported data on irrigation system type, crop rotation, and tillage method, results identify a number of options to increase WP (Grassini and others, 2011a). The most promising include conservation tillage (no-till or strip-till), improved irrigation timing, and switching from surface to pivot irrigation, which facilitates better irrigation timing and irrigation water use efficiency through improved spatial uniformity of applied water. Taken together, adopting all identified options by all farmers in the NRD would reduce NRD irrigation water requirements by 33 percent without a significant reduction in yield (Grassini and others, 2011b).

Farmer-reported data over several years, which includes a large number of observations, provides a powerful tool for evaluating WP and factors affecting it because of the strength of statistical tests and the resulting high degree of confidence in identified options that give

Chart 7

Relationship between Maize Yield and Seasonal Water Supply Based on Farm Data



Notes: Panel A shows relationship between farm grain yields and seasonal water supply from 777 field-years of farmer-reported data from the Tri-Basin Natural Resource District (NRD). Average rainfed yields for the three counties in this NRD were obtained from USDA-NASS (2005–07). Data within shaded area are shown in Panel B disaggregated by irrigation system type or, in Panel C as actual yield and simulated yield with optimal irrigation based on crop simulation in combination with actual weather records and crop management data collected from a subset of 123 fields. The dashed and solid lines are the boundary and mean WP functions from Chart 5. Note scale differences for axes in Panel A versus Panels B and C. Horizontal dashed lines indicate average simulated yield potential (Yp) with current crop management in the Tri-Basin NRD (15.4 milligrams per hectare).
Source: Grassini and others 2011b.

higher WP and associated water savings. For example, while fields with surface or pivot irrigation obtained equivalent yields, applied irrigation was 41 percent less in pivot-irrigated fields (Chart 7, Panel B). Fields under conservation tillage received 64 millimeters (2.5 inches) less irrigation water than those conventionally tilled. The reason for such large water savings with conservation tillage is that crop residues left on the soil surface reduce evaporation and hold winter snowfall in place rather than blowing off into snow drifts along field borders and roads. This results in much more snow melt infiltrating into soil. Such snow melt capture would also be expected in rainfed systems. Additional water savings could be realized by rotating maize with soybean, as maize has a larger irrigation water requirement. Finally, using crop simulation to estimate Yp based on current grower practices for sowing date, hybrid maturity, and plant population shows that a majority of farmers applied more water than needed to reach the biophysical yield ceiling, although about 25 percent of farmers achieved high WP and were within 10 percent of the mean water productivity function line (Chart 7, Panel A).

VII. Genetic Improvement to Increase Water Use Efficiency

Public and private investment in genetic crop improvement over the past 60 years has resulted in hybrids and cultivars that show steady increase in yields. Most of the increase has come from increases in overall stress resistance rather than from raising the biophysical yield ceiling through improvements in photosynthesis or respiration efficiency (Duvick and Cassman; Peng and others; Hall and Richards). Steady improvements result from a "brute force" breeding approach based on thousands of on-farm strip trials across target environments that compare promising lines over several years and select those for commercialization that give highest yields with greatest yield stability. Such selection picks out hybrids and cultivars that are resistant to the wide range of stresses that occur in the target environment; lines that perform well only under a limited set of conditions and stresses are rejected. While biotechnology and bioinformatics can help accelerate the selection process, they have not yet significantly improved drought resistance. Indeed, current state-of-the-art genetic engineering allows the manipulation of single genes, and greatest success has come from modifying plant traits under single-gene control. Resistance to a single disease, insect pest, or herbicide are all traits that can be governed by a single gene. It is therefore no wonder that commercialization of transgenic (GMO) cultivars and hybrids have thus far only involved such single-trait genes. In contrast, complex traits like yield potential, photosynthesis, respiration, nitrogen fixation, nitrogen fertilizer efficiency, and drought are all controlled by scores or even hundreds of genes, each under finely tuned regulation to optimize performance across a wide range of environmental conditions. Modifying and improving on such fine tuning using biotechnology is currently a bridge too far.

Evidence in support of the above proposition comes from recent efforts and enormous investments by large seed companies to improve maize drought resistance. One major seed company focused its investments on a single-gene approach involving an RNA transcription factor (Nelson and others 2007). Another major seed company focused resources on a "turbo-charged," conventional, brute-force breeding program that involved precision phenotyping, genomics and molecular technologies to evaluate genetic architecture, and genetic prediction methodologies using crop simulation (Cooper and others 2014). Both programs have been underway for at least a decade. So far, the single-gene engineering approach has not resulted in the release of commercial hybrids with significantly improved drought resistance (at least, none that have been documented by peer-reviewed results based on rigorous, large-scale field evaluation). In contrast, the turbo-charged, conventional brute force approach has led to the release of hybrids with improved drought resistance (Gaffney and others 2015). The magnitude of improvement is a modest 6.5 percent, which is in the range of what would be expected from a large investment in a modern, conventional, brute-force breeding. It is, however, an important contribution and continued incremental progress should be expected.

VIII. Summary and Conclusion

Meeting food demand while conserving natural resources is perhaps the single greatest challenge facing humankind. Addressing this challenge requires a substantial acceleration in the rate of gain in crop yields on existing farmland while minimizing the conversion of natural ecosystems for food production. While there is tremendous potential to close current yield gaps on existing farmland, doing so will not likely prevent expansion of crop production area without well-coordinated national policies regarding land use change and perhaps marketplace incentives to discourage sourcing crop commodities from expansion into biodiverse and environmentally sensitive regions. Likewise, there is enormous potential to improve the water use efficiency of irrigated agriculture; however, effective policies and regulations are needed to ensure water resources are not depleted or degraded.

Future improvements can be expected from continued innovations in both agronomic practices and genetic improvement. However, current seed company business models are in question, given a rush to merge among the major multinational seed companies.[3] Likewise, appropriate business models have yet to be developed to take full advantage of "big data" composed of farmer-reported data on crop management, high resolution spatial data on soils and climate, and advances in computing power, remote sensing, communication technologies, and crop simulation models.

Increased investment in agricultural research and development (R&D) is needed, as well as improved prioritization to increase the effectiveness and efficiency of that investment. In particular, there is urgent need for ruthless focus on the dual goals of accelerating crop yield gains while concomitantly reducing negative environmental effects. Unfortunately, such an explicit focus is not currently in place in the United States or within the international agricultural R&D community. Lack of such a focus and adequate funding to support it are the two greatest impediments to ensuring global food security in coming decades.

Endnotes

[1]For rice and wheat, however, stagnating yields cannot be due to lack of access to transgenic crop varieties: to date, none have been approved for commercial production.

[2]Other authors suggest there has been greater progress in raising crop yield potential than suggested here. Much of the difference can be explained by differences in definitions and assessment methods with greater reliance on trends from historical varietal yield trials and contest-winning yields (see, for example, Fischer and others).

[3]Of the five largest international seed companies, DuPont and Dow Chemical are proposing to merge and then spin off their seed divisions (Pioneer International and Dow-Elanco) into a single company; Bayer is attempting to buy Monsanto, which tried (unsuccessfully) to merge with Syngenta in 2015; and ChemChina is attempting a buyout of Syngenta.

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Water Linkages beyond the Farm Gate: Implications for Agriculture

By Bonnie G. Colby

This article provides an overview of water scarcity challenges in economic sectors beyond the farm gate that may affect agricultural water access and costs. The relative importance of other large, water-using sectors varies by region but includes municipal, energy and industrial uses. Energy-intensive sectors in particular need careful consideration due to the water consumption embedded in energy use.

Changes in water demand in other large water-using sectors can affect agricultural water access and water costs. Analyses of competition for agricultural water need to consider not only physical availability and use patterns, but also water costs to users in the form of price paid per unit (if any), pumping, conveyance and treatment costs, and other charges related to water use. Climate change alters both water demand and supply through changes in precipitation, timing and quantity of runoff, and temperature effects. As a result, examining past use patterns and availability is instructive but not predictive of future patterns.

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Changes in water costs can have a significant effect on regional water use patterns. Responsiveness to changes in costs varies across regions and sectors. Water prices and other costs paid by water users often are not under the direct control of policymakers and can be politically difficult to alter. However, well-functioning water markets send a signal of water's value to water users, which facilitates voluntary trading and helps regional economies adapt to scarcity.

Incentive-based agreements to trade water, money, and exposure to risks of shortage play a crucial role in implementing and paying for regional adaptation to drought and climate change. Such agreements mitigate high costs, conflict, and uncertainty over scarce water. The agricultural sector, the largest water-consuming sector in most regions of the world, can play a leadership role in regional adaptation to scarcity. A proactive stance will not only make the agricultural sector more resilient but also help buffer regional economies from disruptions linked to water scarcity.

Section I explores water use and scarcity. Section II considers competition for water across sectors. Section III outlines adaptation mechanisms to water scarcity. Section IV discusses potential effects on the farm sector.

I. Water Use and Scarcity

Climate change alters water demand and supply through numerous mechanisms and has differing effects in different regions (IPCC; Dettinger, Udall, and Georgakakos). Future demand and supply patterns cannot reliably be projected based on past data. Nevertheless, examining data on water use trends provides a starting point for considering adaptation to an uncertain future.

Water use data—withdrawals versus consumptive use

In examining water use among sectors and considering competition for water, it is important to distinguish between water withdrawn for a particular use and water consumptively used. Water consumptively used is no longer available in the watershed in which the use is occurring because it has been evapo-transpired or otherwise made unavailable for reuse.

The figures in this article refer to withdrawals, because that is the only data available over a series of years at global and national scales.[1] Water withdrawals data are useful to an extent, but do not provide a clear picture of the effects of one sector's water use on other sectors. Much of the water withdrawn for household use and for some industrial uses (such as power plant cooling) returns to streams and aquifers and is used again multiple times. When farmers irrigate crops, a portion of the water removed from rivers and aquifers is "consumptively used" (evaporated or taken up by plants) and no longer available for other nearby uses. The portion of irrigation water that is not consumptively used (called return flows) seeps back into surface and groundwater at varying rates and becomes available for reuse (Brauman).

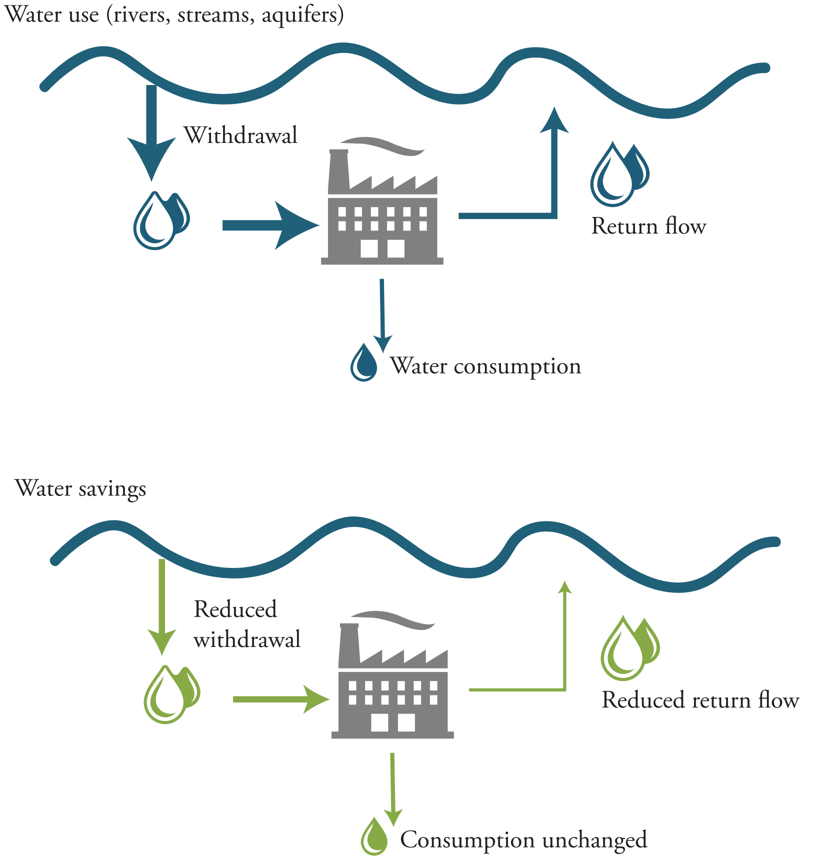
Figures on consumptive use would provide a more accurate picture of "water use" by sector than data on withdrawals, particularly in assessing the effects of water conservation efforts. "Conservation" by cities, farms, and industries does not necessarily reduce consumptive use and "save" water for other uses. The effect of various water conservation practices on consumptive use needs to be evaluated on a case-by-case basis. Figure 1 illustrates this principle. Water-saving devices and practices can reduce the amount of water withdrawn without changing the amount consumed and without improving downstream flow levels (Brauman).

Water withdrawals by sector

Globally and within the United States, water withdrawals for crop irrigation far exceed water withdrawals for industrial and municipal purposes. This is the case for every continent except Europe, where water withdrawals for industry exceed those for agriculture (Maupin and others; FAO 2014). Figures 2 and 3 show water withdrawals by category for the world and for the United States.

Map 1 shows Federal Reserve Districts, which include multiple states. Figures 4 and 5 show water withdrawals by category in two western Federal Reserve Districts. The proportion of urban water withdrawals is much higher in the westernmost Twelfth District, which includes highly urbanized states such as California and Arizona, than in the midwestern Tenth District. Agricultural withdrawals account for the vast majority of water withdrawals in Arizona and California, even though 90 percent of the population lives in urban areas and most of the states' economic activity occurs outside of the agricultural sector.

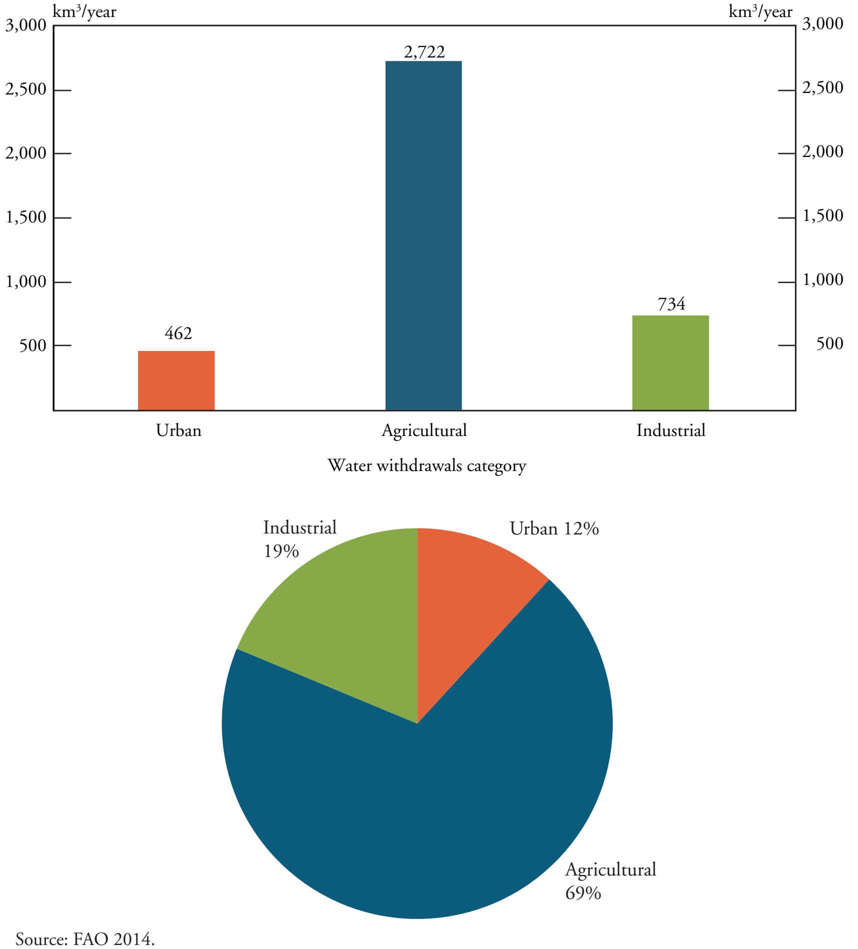
Figure 1
Water-Saving Devices and Practices May Not Reduce Consumptive Use



Note: Graphic adapted from Brauman.

Figure 2

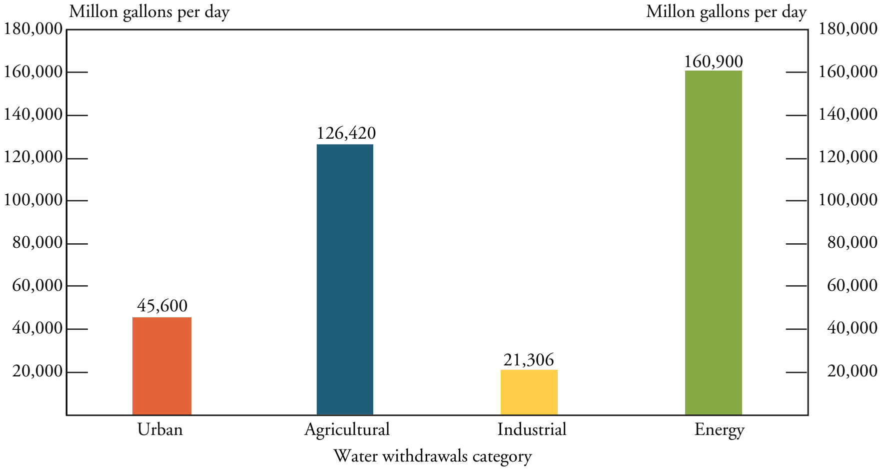
Withdrawals by Category in the World, 2007

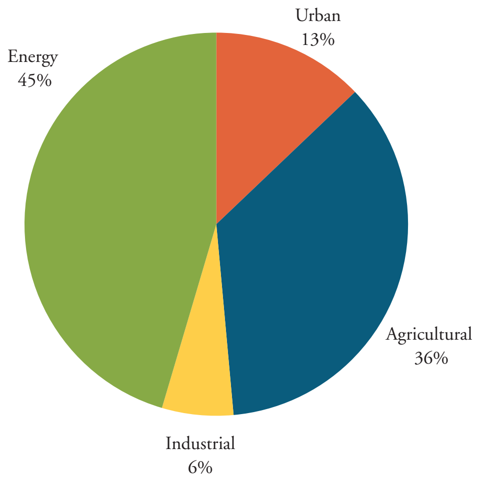


Source: FAO 2014.

Figure 3

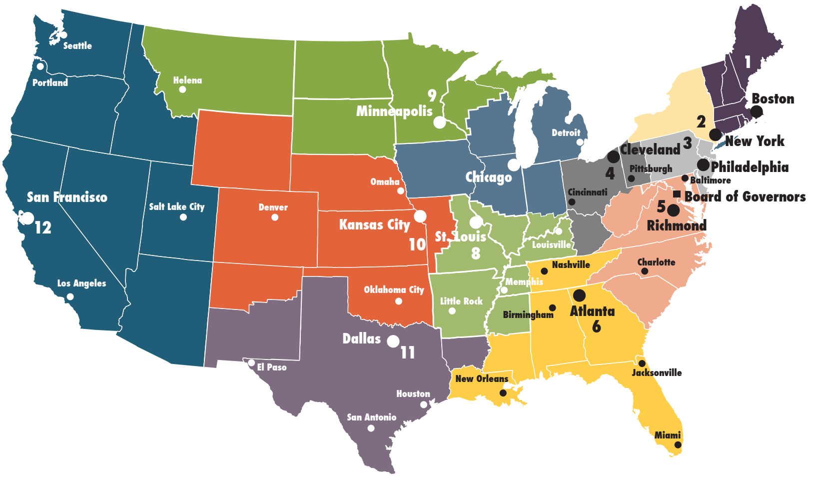
Withdrawals by Category in the United States, 2010





Source: FAO 2014.

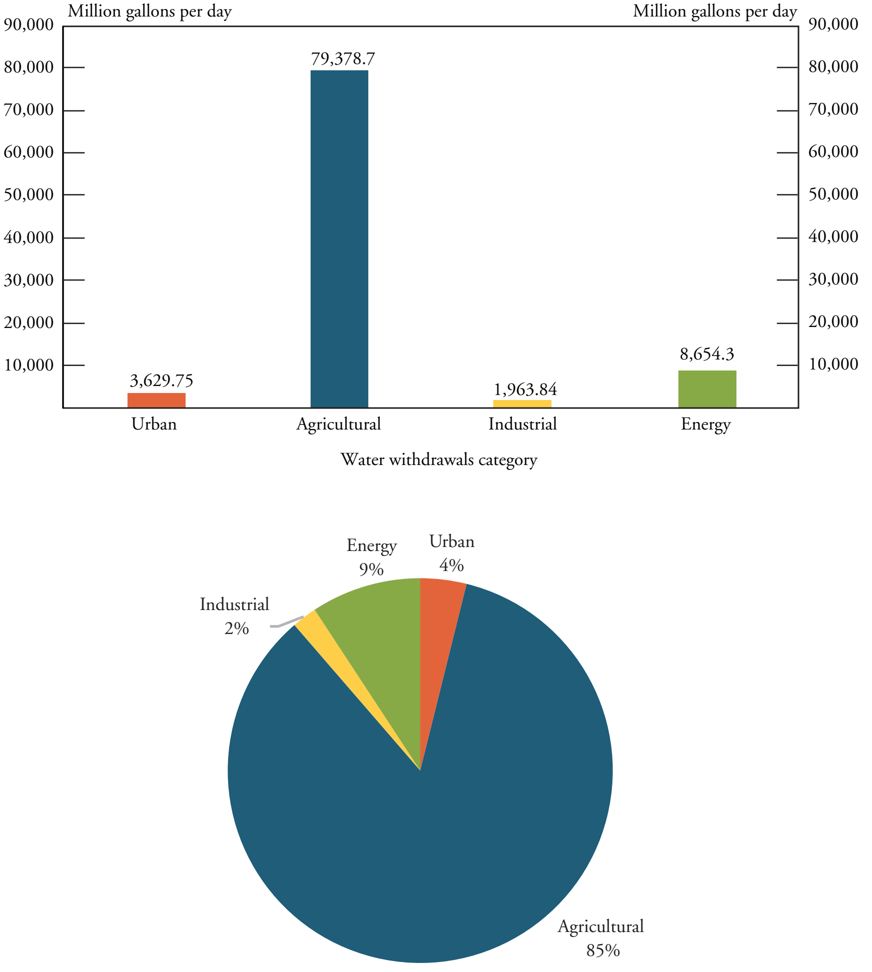
Map 1
Federal Reserve District Map



Source: Board of Governors of the Federal Reserve System.

Figure 4

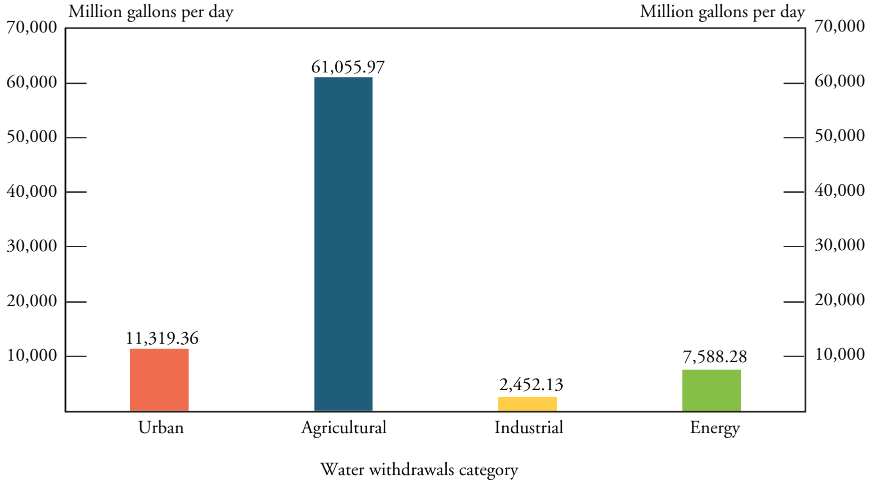
Withdrawals by Category in the Tenth District, 2010

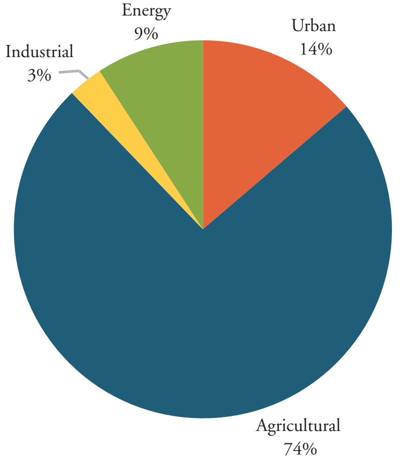


Source: Maupin and others.

Figure 5

Withdrawals by Category in the Twelfth District, 2010





Source: Maupin and others.

Chart 1 shows global water withdrawal data by category over the period 1900 to 2010 alongside world population. The chart shows the energy sector is a significant source of water withdrawals. However, a high proportion of this sector's withdrawals are for power plant cooling water. Most of this water is returned to the hydrological system; only a small portion is consumptively used. Consequently, the thermoelectric sector has a smaller effect on water availability for other uses than Chart 1 suggests.

Chart 2 shows total water withdrawals within the United States from 1900 to 2010, with per capita use included for reference. The decline in U.S. water use per capita, indicated in Chart 2, is driven by many factors, including changes in per capita municipal and industrial use (shown in Chart 3).

By some measures, the United States has experienced significant increases in economic productivity per unit of water withdrawn over time (Chart 4). Donnelly and Cooley define economic productivity of water as "Gross Domestic Product (GDP) generated per unit of water withdrawn," measured on an annual basis and indicated in Chart 4. This measure has increased steadily and significantly over time, indicating that the United States is producing more GDP per unit of water withdrawn.[2]

II. Competition for Water across Sectors

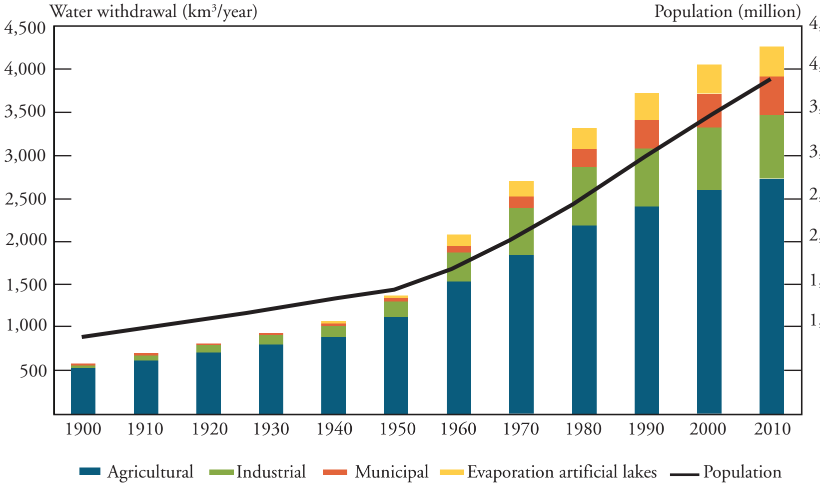
Changes in nonfarm sectors can affect the amount of water available for agriculture, the conditions of its availability, and its cost through multiple pathways. This article considers the urban sector, the energy sector, and other large industrial sectors. These sectors account for the largest water withdrawals (after crop irrigation) globally and in the United States. Changes in water demand or water supply for any of these large water-use sectors have the potential to affect agriculture by increasing regional competition for water.

Another pathway linking water-using sectors involves forward and backward economic linkages through provision of inputs to agriculture and processing of agricultural outputs.[3]

Forward and backward-linked sectors affect agricultural demand for water through their effects on agricultural profitability (for example, changes in the cost of fuel or prices paid by processors to farmers affect farm profitability and thus affect farm demand for water).[4] Moreover, these sectors consume water and so compete directly with farms for

Chart 1

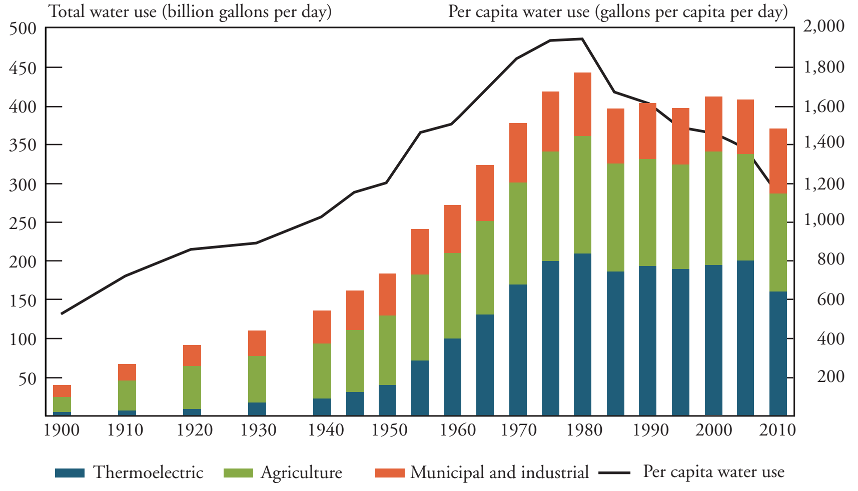
Global Population and Withdrawals by Category, 1900–2010



Source: FAO 2010.

Chart 2

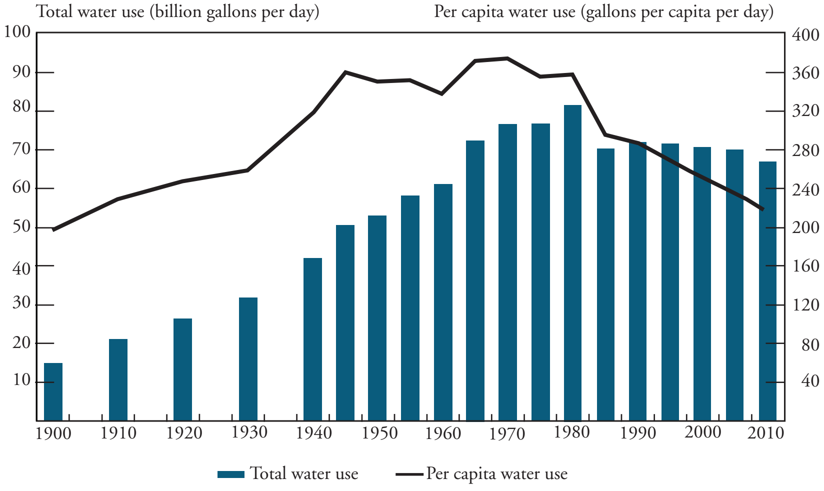
Total Water Use (Freshwater and Saline Water) by Sector, 1900–2010



Notes: Graphic adapted from Donnelly and Cooley. Municipal and industrial (M&I) includes public supply, self-supplied residential, self-supplied industrial, mining, and self-supplied commercial (self-supplied commercial was not calculated in 2000–10). Agriculture includes aquaculture (1985–2010 only), livestock, and irrigation. From 1900 to 1945, the M&I category included water for livestock and dairy.
Sources: Donnelly and Cooley, Council on Environmental Quality, USGS (2014a), and Johnston and Williamson.

Chart 3

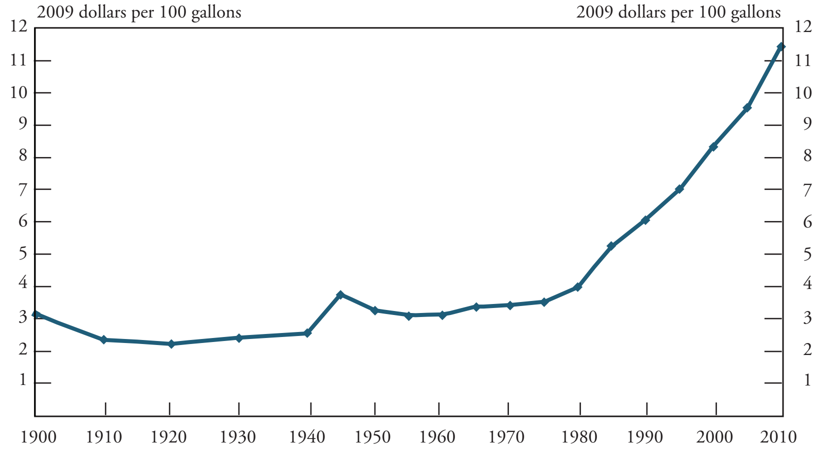
Total and Per Capita Water Use for the Municipal and Industrial Sector, 1900–2010



Notes: Self-supplied commercial water use was not calculated in 2000, 2005, or 2010, which would account for some of the reduction in use that occurred during that period. In addition, the USGS notes that water-use estimates for self-supplied industrial use were more realistic in 1985 than in 1980 and would account for some of the reduction between these years (Solley and others). M&I water use from 1900–45 also includes water for livestock and dairies. Some years include public supply deliveries to thermoelectric; although it was not possible to exclude these deliveries for all years, the years for which data are available suggest this use was relatively small. D.C. was excluded from the analysis due to lack of data.
Sources: Donnelly and Cooley, Council on Environmental Quality, USGS (2014a) and Johnston and Williamson.

Chart 4

Economic Productivity of Water, 1900–2010



Sources: Donnelly and Cooley, Council on Environmental Quality, USGS (2014a) and Johnston and Williamson.

water. These linked sectors consume more water in the same time periods when agricultural water demand is high, thus exacerbating regional competition over limited water.

When agricultural production is more profitable, other factors remaining equal, the value of agricultural water rises and overall agricultural water demand in a region increases. Depending on a region's water allocation mechanisms, higher agricultural demand may cause water prices to rise or conflict over water to escalate. Regional markets in which water can be leased and purchased serve as a "pressure relief valve," providing an alternative to political and legal wrangling over water access.

Economic perspectives on water scarcity, demand, and supply

From an economic perspective, scarcity arises when water is not available to satisfy demand at current costs paid by water users. In common usage, water "demand" refers simply to patterns of water use and "supply" to the physical availability of water. However, when considering competition for water across sectors, it is important to adopt an economic perspective on demand and supply.

Regional water demand functions are temporally and spatially specific, varying across seasons, years, and locations. A demand function indicates how the quantity of water used varies with costs paid by users. The responsiveness of quantity used to cost (price is a component of cost) is measured by "price elasticity of demand." In regions facing reduced supply due to drought, if water costs paid by users do not rise to bring supply and demand back into equilibrium, then excess demand will occur at prevailing prices and other (non-price) allocation mechanisms will be invoked to determine how much water various groups can use. Examples of non-price mechanisms include mandatory curtailment by an administrative agency and legal battles over water access.

Water supply functions capture the relationship between the price water providers receive per unit they supply and the amount of water they supply (price elasticity of supply).[5] The supply function thus conveys changes in the cost per unit of water to those seeking additional water. In regions where growing cities and water-strapped industries look to the agricultural sector to acquire additional water, the net returns per unit of water consumed in growing crops influence the costs other sectors will have to pay to lease and purchase agricultural water (Schuster and others). For example, when hay prices are higher, prices paid to lease water from farmers are higher (Pullen and Colby). Agricultural profitability per unit of water consumed shapes the water supply function for other sectors seeking water from the agriculture sector.

Renewability is an important consideration for a region's water supply. In some locations, precipitation regularly replenishes groundwater. In other regions, such as central Arizona, groundwater reserves were formed eons ago and are not significantly recharged by precipitation. Recent findings indicate that groundwater provides a significant portion of surface flows, estimated at over 50 percent in the Colorado River Basin (Miller and others). Analyses of water scarcity need to consider whether water supplies are renewable or non-renewable.

III. Adaptation Mechanisms to Water Scarcity

Regional adaptations to water scarcity take many forms: altering water rates, facilitating water trading, restricting outdoor water use in cities, mandating conservation practices, and curtailing customary agricultural and industrial uses.

The key role of incentives

While water prices may be the first type of incentive that comes to mind, economic incentives take numerous forms. Some of these incentives are direct and can be used as policy instruments to influence water use—for example, water rates charged to customers of an urban water provider. Other incentives are directly linked to the cost per unit of water used but are not easily altered by policymakers, such as a farmer's cost to pump groundwater from a private well.

Still other incentives operate indirectly. Some of these may be influential but uncertain, such as a potential fine for an irrigation district exceeding its water allotment or a looming court ruling that may impose penalties for failing to provide water for endangered fish. An even more uncertain, yet still influential, set of incentives relates to public values for water to provide recreation opportunities and habitat protection. These values are partially expressed through support for public agency restoration of rivers and wetlands and through successful non-governmental organization (NGO) fundraising for programs that acquire water for environmental needs through leases and purchases and through litigation and lobbying (Water Funder Initiative; Environmental Protection Agency 2015).

To the dismay of economists, water prices charged to urban, agricultural, and industrial water users are not yet widely used as a mechanism to reflect changes in water scarcity. Even when water prices are under the control of municipal policymakers, there is a political reluctance to raise prices for urban water customers.[6] For agricultural and industrial water customers, the costs per unit of water used can be difficult to alter. Water costs paid by farms or industrial users may be based on groundwater pumping and are thus primarily determined by prevailing energy costs. Surface water costs paid by farmers in many areas of the western United States are set under long-term contracts with the Bureau of Reclamation.

In regions where water costs do not vary to reflect changes in demand and supply and where active water trading occurs, signals generated by active water trading are a particularly crucial incentive mechanism. The signal of value transmitted by well-functioning water markets incentivizes water users of all types to consider whether they could reduce their own consumption and earn more by making water available for lease or purchase. Other types of direct incentive signals include rebate programs and cost sharing for water-efficient practices and technologies. In the absence of voluntary reallocation pathways such as rebates and water trading, pressure builds for water-short parties to pursue water access through the courts and administrative processes.

Adaptation mechanisms for urban water use

As Chart 3 indicates, U.S. water use per capita has been dropping since the 1980s due in part to a shift from water-intensive manufacturing to a services sector economy and in part to advances like water-efficient appliances and changes in plumbing codes (Pottinger 2015). However, there is still much room for improvement in outdoor water use, indoor efficiency, water recycling and storm water capture and use. Urban water use per capita is significantly higher in older neighborhoods due to housing with old water-wasting fixtures. Outdoor landscape patterns are changing as programs give homes and businesses incentives to replace lawns with low water use landscaping. In addition, improved measurement and monitoring down to the household use level is growing, though not yet widespread. Smart meters, for example, give households real time information to help adjust their water use in response to incentives.

Although municipal officials are reluctant to raise water rates, many U.S. cities have adopted higher rates and new types of rate structures to generate sufficient revenues to cover their costs in the face of declining per capita use. A recent analysis in California indicates water providers that levy drought surcharges are generally in better financial condition than water agencies that charge flat rates per unit used. The energy sector in California has separated the raw costs of energy itself from the costs of providing energy to customers, and some leaders in the urban water sector are considering how to do this too (Pottinger 2016).

Recycling urban wastewater and capturing and reusing storm water can stretch existing urban supplies. However, capital costs are significant. Loan programs assist in furthering this approach. For example, the California State Water Board facilitates loans for recycled water programs to move the state toward its policy goal of recycling 1 million acre-feet annually by 2020. (Pottinger 2015). Streamlining the permitting process for recycled and storm water projects is another helpful urban adaptation mechanism (PPIC 2015). Referring to Figure 1, it is important to note that not all urban conservation efforts reduce the consumptive use of water in the urban sector and create a net water savings available for other uses. One clear strategy for reducing urban consumptive use is reducing outdoor landscape consumption, a strategy pursued by a growing number of cities that pay households and businesses to remove lawns (Pottinger 2015).

Urban adaptation in the future may include innovative wastewater treatment technologies that generate energy from captured methane to power the water reclamation process as a net zero-energy wastewater treatment system (Pottinger 2016). A zero-energy approach reduces the amount of water consumed in energy production and use.

Smart water-trading platforms are not currently widespread in the United States but can facilitate investment and innovation in water efficiency improvements. For instance, a "smart market" would allow a large industrial user that invests in water recycling (and thus requires less of the high-quality water in their area) to readily lease or sell their "saved water" to other users in the smart market system.

Adaptation mechanisms for industrial and energy sector water use

A large portion of energy used worldwide is consumed capturing, treating, and conveying water to customers and in the course of water use by farms, businesses, and households (Liu and others). In California, the water sector accounts for nearly 20 percent of the state's electricity demand (EI Consultants and Navigant Consulting 2010a and 2010b). Moreover, large amounts of water are consumed in generating energy through electric power plants and petroleum refining. The complex set of feedback between water and energy is sometimes referred to as the water-energy nexus (Fisher and Ackerman). For the purposes of this article, it is sufficient to emphasize that many programs that reduce energy use also reduce water consumption, with specific water savings varying by location and energy conservation practice.

Thermoelectric power plants, the largest withdrawers of water in the United States, use both freshwater and saline water and vary tremendously in the intensity of their water use. An average plant in Arizona uses 0.4 gallons per kilowatt per hour (kWh), while a plant in Rhode Island uses 75 gallons per kWh. The type of cooling system these plants employ determines the difference (Donnelly and Cooley). Overall, the intensity of water use in thermoelectric power production has fallen by over 40 percent in the past three decades. Further improvements can decrease the water withdrawals thermoelectric plants require further. However (harkening to Figure 1), their consumptive use of water will not decrease accordingly and may even increase as higher proportions of power plant withdrawals are used up in the plant cooling process.

Replacing conventional energy sources with renewable energy (wind and solar) has the potential to reduce energy-related water consumption, but this determination needs to be made on a technology and location-specific basis. Moreover, comparisons of water consumption across energy sources need to consider the whole life cycle including construction of facilities and manufacture of equipment, household and business use, and end-of-cycle disposal (Christian-Smith and Wisland).

In addition, hydraulic fracturing ("fracking") to extract oil generates massive demand for water and has become an influential factor in water demand in the regions in which it occurs. Each oil well requires 3 to 5 million gallons of water, and most of this fracking water cannot be reused due to its high salt content. This large, new water demand has caused water trading prices to increase significantly in some regions (Freeman).

Regional water banks and temporary and intermittent water trading

Water banks help ease the effects of water shortages in many areas around the world, including the western United States. Thoughtfully designed water banks provide a way for water users to adapt quickly and cost effectively to changing water supply and economic conditions. Water banks are generally formed through dialogue among stakeholders and water agencies to address specific problems within a well-defined geographic area. Consequently, they typically do not confront the same degree of legal and political obstacles as proposed changes in national or state laws regarding water transfers.

A water bank is a legally authorized entity that facilitates transfers of water on a temporary or intermittent basis through voluntary transactions. Water banks in the United States provide water users with a more reliable water supply during dry years (through voluntary trading) and a means to acquire water when their customary access is curtailed due to regulatory restrictions. In addition, water banks ease the regional economic burden of complying with legal requirements such as interstate compacts or mandatory instream flows for fish and wildlife (Colby 2015). Water banks range in geographic scale from neighboring water users to broad regions that cross state lines (the Arizona Water Bank, for instance, also serves parts of Nevada and California). Water banks in the United States are operated by a wide range of organizations including local, state, and federal government agencies; by NGOs; and by for-profit businesses.

The seasonal and temporary water trading facilitated by a water bank can significantly reduce economic losses due to supply curtailment, thus mitigating the effects of water shortages on regional economies. Specifically, a water bank reduces economic losses that occur when junior rights are curtailed to protect senior entitlements by giving curtailed water users a cost-effective and convenient way to lease water from seniors willing to accept payment for forgoing their water use. Parties enter into water bank transactions voluntarily after weighing the pros and cons. A well-designed water bank makes these arrangements timely and cost effective. Water banks help preserve local water user control and provide choices when external forces such as drought or litigation curtail junior entitlements (Colby 2015).

Water banks can administer various specialized trading arrangements including contingent contracts. Contingent contracts—also called option contracts or dry-year reliability contracts—improve supply reliability for the party paying (the option holder) farmers to fallow cropland under pre-specified shortage conditions. When the contract is triggered, the option holder pays enrolled farmers to temporarily fallow land or to suspend irrigation on land already planted. Some programs pay the irrigation district that supplies water to farmers to cover district-level costs of accommodating a fallowing program. The magnitude, timing, and split of payments between irrigation districts and their member farmers are all determined by negotiations.[7] Contingent contracts are useful in improving supply reliability for junior water users while maintaining a typical agricultural base in average and above-average water supply years. The intermittency of irrigation reductions reduces third-party economic effects as compared with the permanent purchase and retirement of irrigated lands.

Water banks operate in many western U.S states and vary with the regional problems they were created to address. In California, water agencies have actively stored groundwater for local water users for decades to enhance supplies of surface water. Water banking there now also involves storing water underground for more distant parties. Some southern California water banks built up reserves of several million acre-feet, and the large quantities of water they supplied during the drought of the late 2000s dwarfed quantities provided to ameliorate drought effects through other voluntary trading mechanism (Hanak and Stryjewski).

In most U.S. water banks, water is provided through reductions in agricultural consumptive use. Farmers and agricultural districts are key participants in designing and implementing water banks. Native American governments hold quantified senior water rights in many parts of the western United States and participate in water leasing and banking (Colby and others; Thorson and others).

IV. Potential Effects of Competition for Water on Agricultural Water Access and Cost

To recap, competition for water can affect farm water availability and costs. This occurs through multiple pathways, including voluntary trading (with market price signaling changes in water's value) and forced changes in farm water costs and access as a result of administrative and legal processes.

In the United States, legal and political considerations limit the circumstances under which farmers can be required to relinquish water entitlements to make water available for other users. However, court rulings and administrative proceedings sometimes do reduce the amount of water available for on-farm use (McClintock; Zaffos). The pressure for involuntary reallocation intensifies during periods of extended drought and during conflicts over water for endangered species, water quality protection, and reliable urban supplies.

Regional water trading systems provide an important "pressure relief" mechanism to reduce reliance on litigation as a strategy to reduce water available for farming. Policies that provide mechanisms for water to be purchased or leased from farms and irrigation districts and transferred to urban and environmental needs provide an alternative to high-cost and high court battles over water. In some regions, extended litigation and administrative proceedings over water allocation still occur alongside water market transactions. Nevertheless, well-designed water trading mechanisms provide flexible, transparent, and cost-effective ways to move water in response to drought, changing economic circumstances, and special needs.

Regional water trading allows farmers and agricultural districts to benefit directly from rising water values by leasing and selling their water entitlements. They also are exposed to higher costs if they need to enter the market to lease or purchase water. Given that agricultural interests hold large senior entitlements in many areas of the western United States, agricultural entitlement holders will more commonly participate in trading as potential sellers/lessors of a valuable asset rather than as buyers/lessees. The record of water transactions in the western United States demonstrates that agricultural sellers and lessors typically command a price that far exceeds the net returns of on-farm water use (Wichelns; Colby 2015).

Changes in water transaction prices in regions with active markets

Examining past patterns of change in water values indicates how competition for water across sectors can affect agriculture. Statistical analyses of water transaction patterns indicate water demand in other sectors can affect the agricultural sector in several different ways. First, farmers and agricultural districts seeking to lease or purchase water face prices influenced by other sectors. Second, the opportunity cost of water used in agriculture is tied to the prices at which water is traded in regional markets. As market prices signal a higher value per unit of water, farmers with tradable entitlements weigh the returns they can earn from leasing or selling water against the returns they expect to earn growing crops.

Loomis and others examine water market transactions specifically for environmental purposes in the western United States over the period 1995 to 1999. They find that lease values were similar to values estimated for instream flows using non-market valuation techniques and that environmental values exceeded agricultural values for water in specific locations. Brookshire and others analyze statistical patterns in water trading in sub-regions of Arizona, New Mexico, and Colorado. Their econometric analyses find that population change, per capita income, and drought indices have a statistically significant effect on the price at which water is traded, with higher trading prices in drier years.

Bjornlund and Rossini examine the price and quantity of water allocations traded in parts of Victoria, Australia. Results indicate that the most important determinants of water price and volume are seasonal allocation levels, rain, and evaporation. The authors find that irrigators make good use of water markets to manage their variable water supply.

Brown's econometric model of western United States water transactions examines water sales and leases and includes transactions for municipal, urban, or environmental purposes in 14 western states. The results suggest higher lease prices occur in drier time periods, in counties with larger populations, and for municipal and environmental uses. The results for water sales suggest that higher sales prices are related to municipal use, surface water, smaller county populations, and smaller volumes of water traded.

Pullen and Colby's statistical models identify water right seniority and factors influencing agricultural profitability (such as hay prices) as key influences on transaction prices. Jones and Colby analyze hundreds of water leases across four western states (Arizona, California, New Mexico, and Utah) over a 29 year period. Statistically significant variables influencing lease price include per capita income, drier weather, and population growth.

Basta and Colby's econometric models of hundreds of western U.S. water transactions over 1987 to 2010 include urban housing price indices, urban area population, and drought indices. Although each regional model is unique, the urban housing price index is positive and statistically significant in all models. The volume of water involved in a transaction and urban population change is significant in all models as well. While the influence of drought on transaction price varies across areas, drought in the area of a city's water supply origin has a more consistent influence on transaction price than drought in the urban area itself. Hansen, Howitt, and Williams develop econometric models encompassing thousands of western U.S. water sales and leases and find that agricultural production levels and land values influence market activity, as do measures of drought and water supply variability.

Although water trading in the western United States is limited in geographic scope, analyses of areas with several decades of active transactions suggest the potential effect of trading is increased competition for water in agriculture. Drought, changes in urban economic activity, population changes, and changes in farm production and profitability all influence water transaction prices and thus the water value signals transmitted to farmers.

V. Conclusions

This overview article introduces themes raised in the complex interrelationships between agriculture and other water-using sectors and between climate change, the energy-water nexus, water scarcity, and competition and adaptation mechanisms.

The agricultural sector has a unique opportunity to shape adaptation to water scarcity. Taking a position that the best defense is a proactive offense, agricultural organizations and water districts are developing collaborative partnerships and risk-sharing arrangements with other large water users. Farmers and agricultural organizations fruitfully propose and support state and federal policy reforms that establish water banks and other innovative forms of water trading that address agriculture and other sectors' water needs and equitably consider potential effects on third parties (Family Farm Alliance; Colby 2015). Agricultural districts are key players in water banks and other innovative mechanisms to adapt to water scarcity (Marshal and others; Colby 2015). These efforts further water trading as a regional pressure relief valve and reduce the impetus for legal and political maneuvers to curtail agricultural water access.

Endnotes

[1]It is possible to calculate consumptive use by sector for specific regions using detailed region-specific data and models, but this is not within the scope of this overview paper.

[2]GDP has been criticized as a measure of economic output for neglecting to include changes over time in natural capital such as water and air quality and habitat. This indicator of water's economic productivity could usefully be refined (with considerable work) to reflect a broader spectrum of economic considerations and to reflect consumptive use by sector rather than water withdrawals. Nevertheless, this indicator shows significant change over time in patterns related to U.S. economic production and water use.

[3]Backward-linked sectors provide inputs to agriculture such as fertilizer, seed, farm equipment, fuel, and water. Forward-linked sectors purchase crops and livestock and add value to farm outputs through processing and distribution. Examples include cotton gins, feedlots, textile mills, and grain-processing facilities.

[4]Due to the brief and non-technical nature of this article, the focus here is on competition over water rather than on specific forward and backward linkages.

[5]Many water providers cannot provide additional amounts when users' willingness to pay per unit provided increases due to long-term contracts (as with Bureau of Reclamation water projects) and other restrictions. Consequently, a regional water-supply function may appear as a series of upward rising steps with each step representing a quantity of water provided by a specific provider at a specific price to users.

[6]Recently, however, many U.S. cities have had to significantly increase water charges to ensure revenue sufficiency in the face of declining use (Walton).

[7]For examples of these types of arrangements, see O'Donnell and Colby; Colby 2015.

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Investing in Adaptation: The Challenge of Responding to Water Scarcity in Irrigated Agriculture

By Susanne M. Scheierling and David O. Treguer

Water scarcity is increasingly acknowledged to be a major risk in many parts of the world (World Economic Forum). Projections indicate that water-related problems may significantly worsen over the next several decades due to rising water demands as a result of demographic, socioeconomic, and technological changes, and due to the effects of climate change (World Water Assessment Program; Jiménez Cisneros and Oki). Significant advances in water management and more integrated policymaking, including increased investment in adaptation measures, will be necessary to reduce the risk of dramatic consequences for economic growth and environmental sustainability.

The need for water-related adaptation measures will probably be most critical in the agricultural sector, especially in irrigated agriculture. Irrigated agriculture accounts for about 70 percent of total freshwater withdrawals worldwide (Molden and Oweis). Water use in agriculture, especially in semi-arid and arid regions, tends to be closely linked

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to water scarcity, and improvements in agricultural water management would have large implications for overall water management. In addition, water use in agriculture tends to have relatively low net returns compared with other uses (Young 2005). Thus, as water becomes scarcer and supply augmentation more expensive, other users tend to turn to agriculture as a potential source of water. At the same time, agriculture is expected to increase production—and concomitantly agricultural water use—to meet the likely demands from a growing population with changing diets (Alexandratos and Bruinsma). The effects of climate change will further increase the need for water-related adaptation measures and add layers of complexity for agriculture (Pachauri and Reisinger; Jiménez Cisneros and Oki). Freshwater resources will be affected due to altered amounts and frequencies of precipitation—especially in semiarid and arid areas that often already experience water scarcity. Due to more intense precipitation and prolonged dry periods, rainfed cropland may need to be irrigated. Crop growth more generally will be affected not only by changes in precipitation but also by changes in temperature, evapotranspiration, and soil moisture.

To at least partially respond to these challenges, the agricultural sector is considering and increasingly applying a wide range of water-related adaptation options (Noble and Huq). Adaptation investments can occur at different scales, from the field and farm levels to the policy and institutional levels (Porter and Xie). Given the complexity of the challenges, adaptation measures may have one or more of three different objectives (Scheierling and Treguer). The two key objectives are maintaining or increasing agricultural production, in some cases without worsening water scarcity, and conserving agricultural water in response to pressures to reallocate water to other uses such as the environment or coping with water scarcity. A third objective that may be linked to the other two is increasing, or at least maintaining, agricultural net revenues. However, in many cases, the objectives of adaptation investments are not clearly stated and their broader results not closely assessed. This adds to the constraints facing adaptation measures, limits their effectiveness in implementation, and may even lead to unintended or counterproductive outcomes. This article aims to further shed light on these issues.

Section I highlights some of the unique characteristics of water that complicate responses to water scarcity in irrigated agriculture. Section

II illustrates the links between irrigated agriculture and water scarcity with data at the global level. This is followed by a discussion of two broad categories of adaptation measures. Section III examines engineering and technical measures, which are probably the most common adaptation measures and usually applied on-farm with private investments and often supported with public subsidies or technical assistance. Section IV focuses on policy and institutional measures. While both types of measures may pursue any or all of the three key objectives, engineering and technical measures tend to contribute to the first and, in particular, the third objective; policy and institutional measures have an important role to play in achieving, in particular, the second objective. Section V presents recommendations going forward.

I. Characteristics of Water Important for Considering Adaptation Measures

Water has unique characteristics that distinguish it from most other resources and commodities and pose significant challenges for selecting appropriate adaptation measures (and for designing water policy in general). Based on Young (1986; 2005), who provides a full discussion of these characteristics, this section focuses on the features that may be most important to keep in mind when considering adaptation measures.

A key physical attribute of water is its mobility. Typically found in liquid form, water tends to flow, evaporate, and seep as it moves through the hydrologic cycle. This makes it a high exclusion cost resource, implying that the exclusive property rights, which are the basis of a market or exchange economy, are relatively difficult and expensive to establish and enforce.

Water supplies, although generally renewable, also tend to be relatively variable and unpredictable with regard to time, space, and quality. Local water availability usually changes systematically throughout the seasons of the year and over longer cyclical swings, with climate change now affecting both short- and longer-term supply trends as well as the extremes of the probability distributions—specifically, floods and droughts. Due to these supply variations, as well as variations in local demand, water-related problems are typically localized, and interventions, such as adaptation measures, often need to be adapted to the local context.

The physical nature of water, combined with supply variability, causes unique interdependencies among water users that become more pervasive and complex as water scarcity intensifies. Water is rarely completely "consumed" in the course of human consumption or production activities. In irrigated agriculture, for example, it is not unusual for half of the water withdrawn from a water source to be returned to the hydrologic system in the form of surface runoff or subsurface drainage (an even larger proportion is typically returned from municipal and industrial withdrawals). Other users, particularly downstream users, are thus greatly affected by the quantity, quality, and timing of releases or return flows of upstream users.

These interdependencies among water users have several implications, especially for on-farm adaptation measures. They make it difficult to derive water-related insights from what is observed on the field or farm level for the overall effects at the basin level. They lead to externalities (or uncompensated side effects of individual activities) where the full costs of the activities are not incorporated in individual users' decisions and outcomes for society are suboptimal. Thus, there is a need for public policy to complement individual activities and orient them toward more desirable outcomes from a social point of view.

II. Irrigated Agriculture and Water Scarcity: A Global View

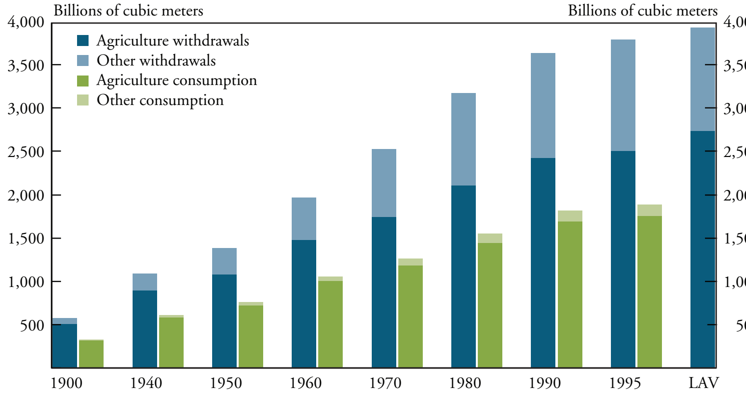
Establishing a link between irrigated agriculture and water scarcity is difficult due to a number of factors. Among them are not only the special characteristics of water discussed in Section I, but also the definition of water scarcity as well as the availability of data related to current and projected agricultural water use, especially at the global level.

Central role of water use in agriculture

As a first step, it is useful to keep in mind the global trends in agricultural water use. Based on data from Shiklomanov and Rodda and the Food and Agriculture Organization of the United Nations (FAO 2016a), Chart 1 shows the development in agricultural withdrawals, total water withdrawals, and consumption since 1900.[1] The agricultural sector has continually accounted for the largest share of total water withdrawals. From 1900 to 1995, the agriculture share decreased from 89 percent of total water withdrawals to 66 percent; more recently, it

Chart 1

Global Trends in Agricultural and Total Water Withdrawals and Consumption



Note: Blue bars show withdrawals, and green bars show consumption. LAV=latest available value.
Sources: Authors' calculations based on Shiklomanov and Rodda; FAO 2016a.

increased to 70 percent (FAO 2016a). Almost all of total water consumption has been agricultural consumption, with the share slightly decreasing from 97 percent in 1900 to 93 percent in 1995. Agricultural consumption as a share of agricultural water withdrawals increased from 63 percent to 70 percent over the same period. Overall, both total and agricultural water withdrawals have increased dramatically since 1900, but since about 1980, their rates of growth have declined. Contributing to this outcome is that in most Organisation For Economic Co-operation and Development (OECD) countries, total and agricultural water withdrawals have tended to remain stable or decrease (OECD 2013).

Table 1 presents data on the 10 countries with the largest annual agricultural water withdrawals based on the latest available data from FAO (2016a; 2016b). These countries are also responsible for the largest total withdrawals. The 10 countries are among those with the largest areas equipped for irrigation and among the 17 most populous in the world (World Bank Group).[2] Except for the United States and China, the 10 countries' percentage of total water withdrawals allocated for agriculture is larger than the worldwide average of about 70 percent. When dividing the amount of agricultural water withdrawals by the area equipped for irrigation, half of the 10 countries are shown to withdraw an irrigation depth of 1 meter or more for their respective area equipped for irrigation. The lowest value of 0.5 meter is shown for China, followed by 0.7 meter for the United States.

Table 1
Countries with the Largest Agricultural Water Withdrawals

Country	Agricultural water withdrawals (billion cubic meters)	Total water withdrawals (billion cubic meters)	Agricultural water withdrawals as percent of total water withdrawals (percent)	Area equipped for irrigation (million hectares)	Area equipped for irrigation as percent of agricultural area	Agricultural water withdrawals per area equipped for irrigation (meters)
India	688	761	90	67	37	1.0
China	358	554	65	69	13	0.5
United States	175	486	40	26	6	0.7
Pakistan	172	184	94	20	75	0.9
Indonesia	93	113	82	7	12	1.3
Iran	86	93	92	10	19	0.9
Vietnam	78	82	95	5	42	1.6
Philippines	67	82	82	2	13	3.4
Egypt	67	78	86	4	100	1.5
Mexico	62	80	77	7	6	0.9

Sources: FAO 2016a and FAO 2016b.

When considering all countries with agricultural water withdrawals, a close relationship can be established between agricultural water withdrawals and total water withdrawals as well as area equipped. According to Panels A and B of Chart 2, agricultural water withdrawals are highly correlated with total water withdrawals; specifically, an increase of 1 cubic meter in total water withdrawals is associated with an increase of 0.74 cubic meter in agricultural water withdrawals. According to Panels A and B of Chart 3, agricultural water withdrawals are also highly correlated with the area equipped for irrigation; an increase in 1 square meter of area equipped for irrigation is associated with an increase of 0.77 cubic meter in agricultural water withdrawals.

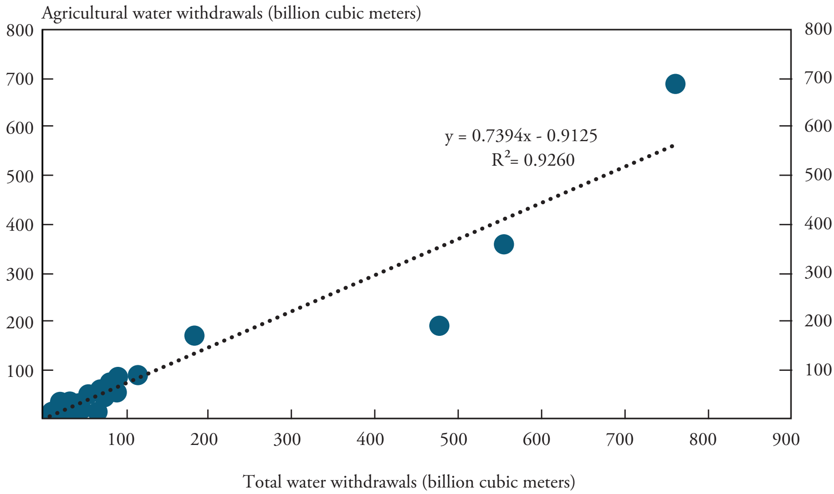
Linking irrigated agriculture and water scarcity

Various definitions of water scarcity have been proposed and different indicators applied (UNEP). One widely used indicator is based on a comparison of total water withdrawals and total renewable water resources at the national level.[3] A country is considered to experience "scarcity" if total water withdrawals are from 20 to 40 percent of total renewable water resources, and "severe scarcity" if this value exceeds 40 percent. Map 1 displays this indicator based on the latest available data

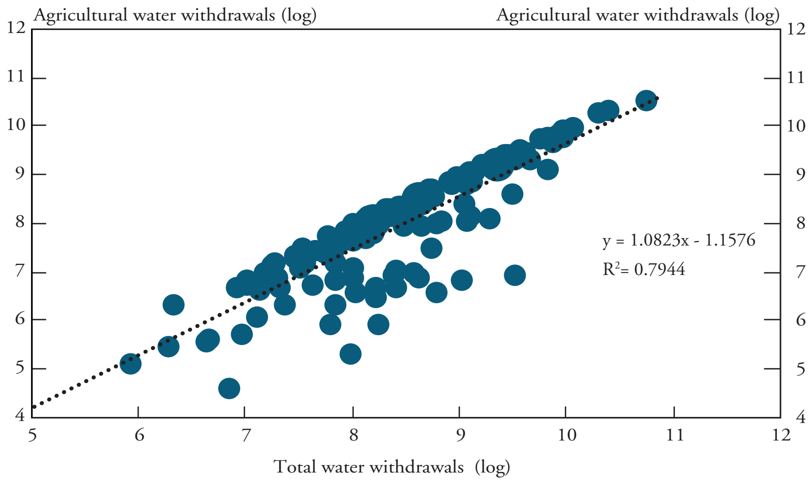
Chart 2

Agricultural Water Withdrawals and Total Water Withdrawals by Country

Panel A



Panel B

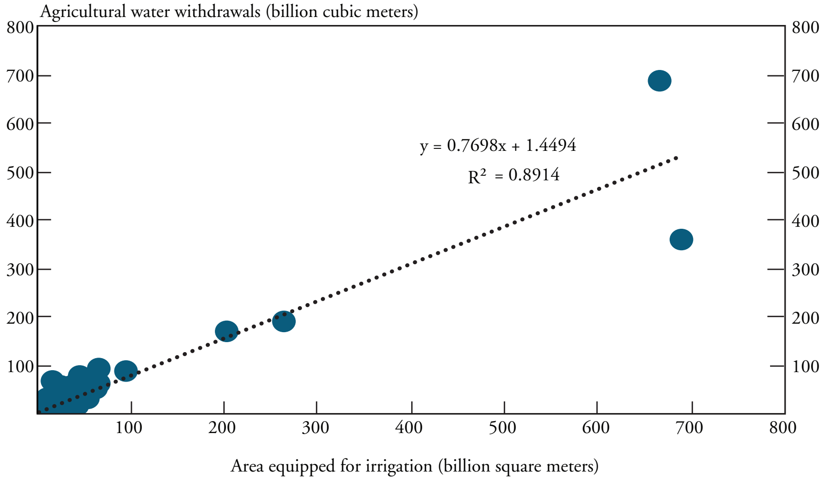


Source: Authors' calculations based on FAO 2016a.

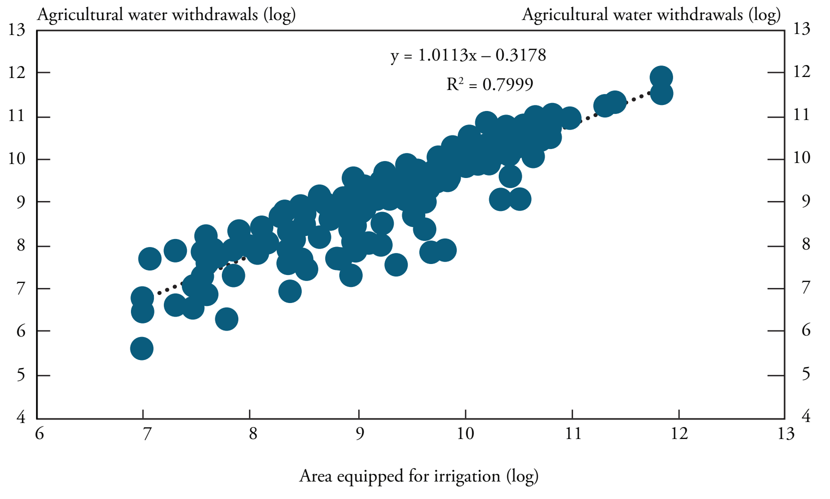
Chart 3

Agricultural Water Withdrawals and Area Equipped for Irrigation, by Country

Panel A



Panel B



Sources: Authors' calculations based on FAO 2016a and FAO 2016b.

from FAO (2016a). Countries in the Middle East and North Africa (MENA) are all shown to experience severe water scarcity. In other parts of the world, including most countries in South Asia and Central Asia, water is also considered scarce or severely scarce. Some countries' water withdrawals are even higher than their total renewable water resources. Saudi Arabia is the most extreme case, withdrawing almost 10 times the amount of renewable resources available and thus relying mostly on nonrenewable groundwater.

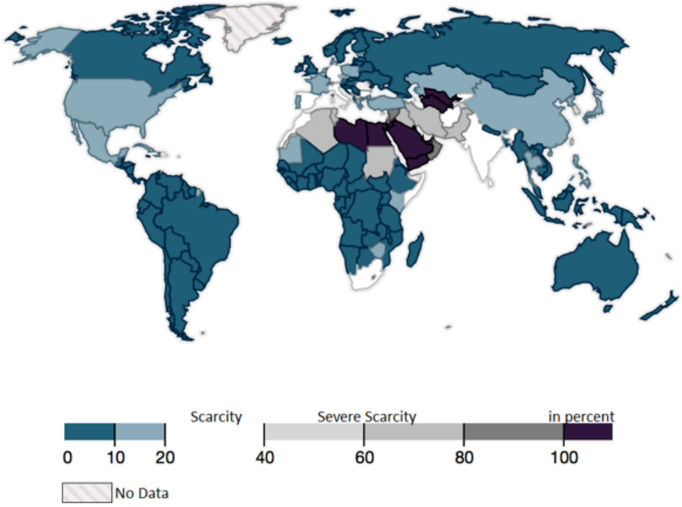
To illustrate the link between water scarcity and irrigated agriculture, we modify the indicator and, instead of total water withdrawals, compare agricultural water withdrawals to total renewable water resources (Scheierling and Treguer). Map 2 shows the data for the modified indicator. The astonishing result is that the classification of countries with "scarcity" and "severe scarcity" is almost the same as in Map 1, even though only agricultural withdrawals are considered. This shows the central role of irrigated agriculture in assessments of water scarcity at the national level. The most extreme cases are in MENA: in Saudi Arabia, water withdrawn for irrigated agriculture alone is more than eight times the amount of total renewable water resources; in Libya, it is about five times, in Yemen one and a half times, and in Egypt slightly more than the amount of total renewable water resources.

Some caveats apply to both indicators. On the one hand, they may underestimate water scarcity: since they refer to the national level and apply annual water data, they do not indicate water scarcity situations that may occur at the regional or local levels (especially in large countries such as China) or during the year. They also do not consider water quality issues or water requirements for the environment. On the other hand, they may overestimate water scarcity, since data on withdrawals would include the reuse of return flows that can be substantial in many cases (such as along the Nile in Egypt).

The available data do not allow for an analysis of how changes in agricultural water withdrawals have affected water scarcity over time. However, a look at historical data on area equipped for irrigation can provide some insights (FAO 2016b). Globally, the area equipped for irrigation increased from 164 million to 324 million hectares (ha) over the past 50 years. Chart 4 shows the trends by geographical region (excluding high-income countries) from 1962 to 2012. The biggest

Map 1

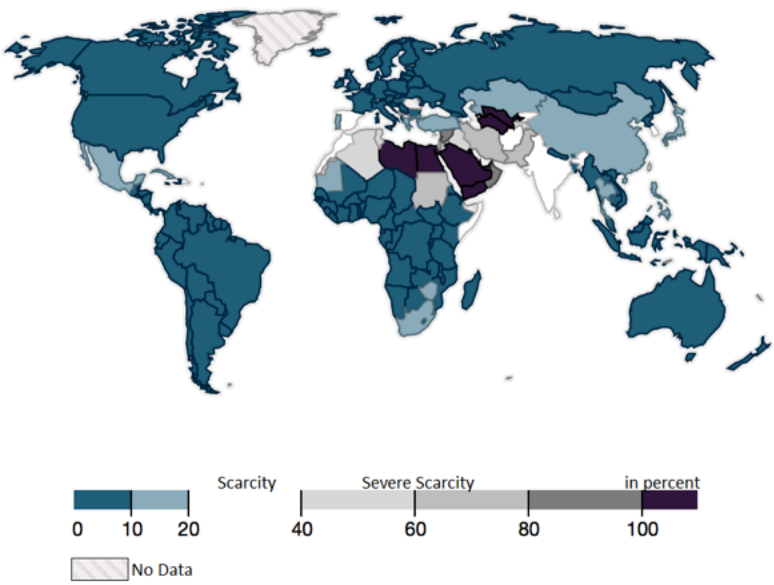
Total Water Withdrawals as Percent of Total Renewable Water Resources



Source: Authors' calculations based on FAO 2016a.

Map 2

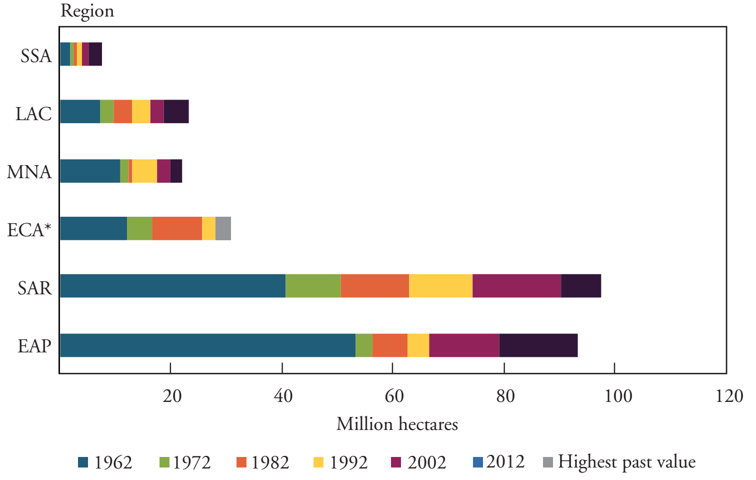
Agricultural Water Withdrawals as Percent of Total Renewable Water Resources



Source: Authors' calculations based on FAO 2016a.

Chart 4

Trends in Area Equipped for Irrigation by Region, 1962–2012



Notes: SSA=sub-Saharan Africa, LAC=Latin America and the Caribbean Region, MNA=Middle East and North Africa, ECA=Europe and Central Asia, SAR=South Asia Region, EAP=East Asia and Pacific. ECA* includes data for the USSR/Russian Federation.
Source: Authors based on FAO 2016b.

growth occurred in South Asia, followed by East Asia and the Pacific. Only Europe and Central Asia have seen a reduction in area equipped for irrigation since the 1990s, mostly due to reductions in the countries of the former Soviet Union.

The largest percentage increase in area equipped for irrigation of any country occurred in Saudi Arabia (from 0.3 to 1.6 million ha), followed by Libya (from 0.1 to 0.5 million ha) and Yemen (from 0.2 to 0.7 million ha). These three countries are now experiencing some of the most severe water scarcity. Large area increases, in both percentage and absolute terms, also occurred in India (from 26 to 67 million ha), a country now considered water scarce, and in China (from 45 to 68 million ha).

Projected trends

Agricultural water withdrawals will continue to be a major factor shaping the water situation worldwide, particularly given the expected need for an increase in irrigated area due to rising demand for agricultural products. Projections vary depending on the models employed and the assumptions and scenarios used. For example, projections by the FAO indicate that agricultural production in 2050 would have to be 60 percent higher than in 2005/2007, and irrigation water withdrawals would need to increase from 2,761 to 2,926 billion cubic meters per year to meet the likely demand (Alexandratos and Bruinsma). Considering the historic data in Chart 1 and rapidly growing water demands, especially from the municipal and environmental sectors, this projected increase—which is based on rather optimistic assumptions—is quite worrisome.

Projections become even more dire—and more uncertain—when the effects of climate change are taken into account (Elliott and others). Such projections suggest that by the end of this century, renewable water resources may allow a net increase in irrigated agriculture in some regions (such as the northern and eastern United States and parts of South America and Southeast Asia), while in other areas (such as the western United States, China, MENA, and Central and South Asia), the previous expansion from rainfed to irrigated agriculture would need to be reversed.

III. Investing in Engineering and Technological Adaptation Measures

Probably the most common adaptation investments for responding to water scarcity in irrigated agriculture are engineering and technological measures. These measures are usually applied on-farm and financed with private investments, often supported with subsidies or technical assistance. They include more capital-intensive irrigation technologies, improved seeds, and precision farming to help optimize the use of water and other inputs tailored to local conditions. As water scarcity or the variability in supplies increase, large private and public sector investments are being made in many countries for such adaptation measures.

Conversion to more capital-intensive irrigation technologies as a popular measure

One popular and widely adopted measure is the conversion to more capital-intensive irrigation technologies. These technologies increase the "efficiency" of irrigation water on a field by reducing evaporation and losses from surface runoff or subsurface drainage. The implicit assumption is that a switch to such technologies will allow farmers to maintain agricultural production with less water withdrawn and applied to a field while at the same time conserving water for reallocation to other uses.

In pursuit of the objective of water conservation, farmers in both advanced and emerging market economies often receive financial and technical assistance from the public sector to help them convert to more capital-intensive irrigation technologies. For example, the U.S. Department of Agriculture has long provided such assistance to farmers under the Environmental Quality Incentives Program first authorized in the 1996 Farm Act (USDA). The Incentives Program provides cost-sharing of up to 75 percent to help farmers install more capital-intensive irrigation equipment such as sprinklers and pipelines, with the aim of conserving ground and surface water resources. Subsidies of over $10 billion have been provided under the program for technology adoption, including for water conservation (Wallander and Hand). Similarly, Morocco is currently implementing the National Irrigation Water Saving Program, launched under the government's Green Moroccan Plan in 2008 and supported with planned public investments of $4.5 billion. The Moroccan program aims to conserve irrigation water by helping convert about 550,000 ha of agricultural land from surface to drip irrigation by 2020, with subsidies of up to 100 percent for farmers' on-farm investments (Badraoui).

Effect on water scarcity when return flows are important

In many contexts, on-farm investments in "irrigation efficiency" contribute more to the objective of maintaining or increasing agricultural net revenues (and, frequently, to the objective of maintaining or increasing production) than to the objective of conserving water for alternative uses. For the United States, an increasing number of studies show that while such investments may reduce on-farm water applications, they do not necessarily provide real water savings and thus may not have much effect on water scarcity. In contexts where return flows matter to downstream uses, real water savings (that is, a "new supply" of water for reallocations) would require a reduction in water consumption. In many instances, the conversion to more efficient irrigation technologies may have the counterproductive effect of increasing consumption, thus worsening water scarcity.

Furthermore, in some situations, the introduction of more efficient irrigation technologies may even lead to increases in the amounts of water withdrawn and applied. In energy economics, this is known as the rebound effect, or Jevons paradox, whereby efficiency increases in the use of a resource result in more being demanded (Alcott). In the field of water management in agriculture, the rebound effect is increasingly being discussed—usually in connection with the risk of increasing water withdrawals and applications (Chambwera and Heal; OECD 2015a). However, the rebound effect can also be observed—and may be even more prevalent—for consumption.

Hartmann and Seastone were among the early water economists who drew attention to the interdependencies among water users and the resulting externality problems. They pointed out that only part of the water withdrawn from a river is used consumptively, whereas the non-consumptively used part typically returns to the stream as runoff or percolates into the underlying groundwater deposits and becomes available for pumping. Using a simplified river system as an example, they illustrated that any change in these return flows (in magnitude, timing, or quality) may affect downstream users. Huffaker and Whittlesey (1995) and Whittlesey (2003) use similar examples to show that improvements in on-farm irrigation efficiency reduce withdrawals and applications, but that in the presence of significant usable return flows, this effect does not produce additional water. If the "saved" water is used to increase irrigated acreage, consumption may even increase.

Subsequent studies based on normative models show that by converting a larger share of water applications into consumption, more efficient irrigation technologies reduce the effective cost of consumption. Farmers optimally respond to this cost change by increasing consumption and irrigated acreage, all else equal. Furthermore, these changes may decrease or increase the demand for applied water (Whittlesey). Scheierling, Young, and Cardon (2006) show that a subsidy policy may increase consumption even in places where an expansion of irrigated land beyond the original land to which a water right applies is not permitted, such as under Colorado's prior appropriation system. This would occur when farmers find it profitable to alter the crop mix or change the irrigation schedule. Ward and Pulido-Velazquez analyze the effect of subsidies by applying an integrated basin-scale programming model to the Upper Rio Grande Basin and find that while water applied to irrigated lands may fall, overall consumption increases. Where return flows are an important source of downstream water supplies, water right holders that depend on these flows would be negatively affected. Contor and Taylor show more generally that whenever an improved irrigation technology reduces the non-consumed part of applied irrigation water, consumption will increase at any non-zero marginal costs for water.

In a study based on an econometric approach, Wallander and Hand use farm-level panel data from national samples of irrigators to estimate the effects of the Environmental Quality Incentives Program on water conservation—in particular, changes in water application rates and irrigated acreage. Results suggest that for the average farm, payments may have reduced water application rates but also may have increased total water use and led to an expansion in irrigated acreage.

Effect on water scarcity when return flows are not important

In river basins, where return flows constitute a considerable part of the downstream supplies, a reduction in consumption is the appropriate measure for water conservation; the measure may be different, however, in cases where return flows are less important. For example, return flows would be less important in a region irrigated from a deep aquifer, such as the Ogallala beneath the Great Plains, where return flows to the aquifer are minimal and very slow. Water conservation may then be appropriately measured by reductions in withdrawals. Studies have shown that the switch to more efficient irrigation technologies in such a situation may increase or decrease withdrawals depending on the context; empirical analysis is required to determine the effect.

Various approaches to generating empirical estimates have been used for the Ogallala region, not least because of the relatively good availability of water-related data. For example, Peterson and Ding apply a risk-programming model to corn production on the Kansas High Plains and find that even under simplifying assumptions, the effect of an efficiency change on withdrawals is ambiguous. Their results suggest that a conversion from flood to subsurface drip irrigation would decrease both irrigation application per acre and the volume of groundwater withdrawn. A conversion from flood to center pivot, on the other hand, would increase irrigation applications per acre but decrease the overall volume pumped, because fewer acres would be irrigated. The latter conversion would also be cost-effective.

In an econometric evaluation, Pfeiffer and Lin use panel data from over 20,000 groundwater-irrigated fields in western Kansas from 1996–2005, when farmers converted from flood irrigation or traditional center pivots to more efficient center pivots with drop nozzles—supported by subsidies from state and national sources, including the Environmental Quality Incentives Program. They find that with the conversion, the amount of groundwater pumped and applied to fields increased. This is because farmers tended to shift toward a crop mix with relatively more corn—a more water-intensive crop than the traditional wheat and sorghum—and apply more water per acre. Farmers also irrigated a slightly larger proportion of their fields, and were less likely to leave fields fallow or plant rainfed crops.

These considerations, such as the local context and the relative importance of return flows—illustrated above using the example of more efficient irrigation technologies—are likely to be similarly important in determining the effect of other engineering and technological measures applied on-farm on water scarcity. However, there will also be exceptions. In the case when returns flows are important and the focus is on reducing consumption (while at the same maintaining agricultural production), this would include adaptation measures that directly aim to either decrease evaporation (for example, the application of mulching techniques or conservation tillage) or transpiration (for example, the switch to crop varieties with shorter growing season length).

IV. Investing in Policy and Institutional Adaptation Measures

As water scarcity grows, investments in policy and institutional adaptation measures become increasingly important. These investments may range from raising awareness and fostering innovations to applying economic instruments for balancing water supplies and demands (Noble and Huq). While supply-side measures such as investments in water storage infrastructure and alternative sources of water supplies (for example, desalinized water or treated wastewater) may continue to play a role, the emphasis on demand-side measures is increasing

(OECD 2015a). As engineering and technological adaptation measures applied on-farm are often focused on maintaining or increasing agricultural net revenues and production, policy and institutional measures are essential to contribute to the objective of conserving agricultural water for reallocation to other uses or for coping with water scarcity. Policy and institutional measures also need to promote and ensure private adaptation investments are aligned with this objective.

Measures for facilitating reallocations

Arrangements for water allocation (the apportioning of water among users within and between sectors) can be grouped into price-based or quantity-based measures. With increasing water scarcity, water allocation arrangements need to facilitate transfers of water use (a change in type of use, location, or point of withdrawal) while also protecting affected interests (Young 1996).

Price-based measures—in particular, price incentives involving higher costs of irrigation water—are increasingly considered as a potential tool for reducing water applications. Price measures could encourage farmers to use water more efficiently and make water available for other uses. An economic measure often used to assess the effectiveness of price increases is the price elasticity of the derived demand for irrigation water, indicating the proportional change in water demand for a given change in price. Most studies present price-inelastic demand estimates (Scheierling, Loomis, and Young), and caution against pricing policy. The common argument is that even small reductions in irrigation water applications would require large price increases, which, in turn, would cause large negative effects on agricultural net returns.

Yet as long as farmers have a range of adjustment options (such as changes in crop mix, irrigation scheduling, or irrigation technology), even a price-inelastic demand does not necessarily imply water applications cannot be substantially reduced as the price starts to rise (Scheierling, Young, and Cardon 2004). Even if water prices rose significantly, however, they would not be very effective in reducing consumption. In contexts where return flows are important, volumetric charges would therefore not generate much real water savings. In such situations, it would be more appropriate to encourage farmers to switch to crops with lower seasonal consumption or to dryland crops, possibly with subsidies. Theoretically, irrigation water pricing could be an effective policy instrument if volumetric charges were imposed on consumption. However, to our knowledge, this has so far not been attempted, possibly because the cost of measurement and administration would be even higher than for charges on water applications or withdrawals.

Quantity-based measures, or quotas, can be designed to minimize externalities and to ensure security of tenure and consistent enforcement—and, in principle, to achieve efficient allocation (Young 1995). A number of difficulties, however, including variations in water supply, need to be addressed. An example of a quota system is the prior-appropriation doctrine of "first in time—first in right" in the western United States that assigns entitlements in terms of water withdrawals. An alternative to this concept of "release sharing" is the concept of "capacity sharing" that assigns entitlements as shares of stored water. Capacity sharing has recently been introduced in Australia in response to increased water scarcity.

Exchangeable quotas allow reallocations through water markets. These reallocations may involve permanent or temporary transfers, including water-supply option contracts in which transfers occur only during contractually specified drought conditions. Water markets provide price signals that encourage the movement of water from lower- to higher-valued uses, thus enhancing economic efficiency (Young 1995). As water scarcity increases, more countries are experimenting with water trading (Griffin and Peck). A number of challenges to water trading need to be overcome: addressing externalities and protecting the entitlements of potentially affected third parties, considering non-efficiency goals (such as ensuring access to a certain amount of water per person per day), safeguarding instream benefits (for example, for environmental or recreational purposes), and reducing information and transaction costs for market participants (Young 1986; Griffin and Peck).

Water markets have mostly been observed so far in countries with strong legal, institutional, and regulatory arrangements. In many emerging market economies, other reallocation mechanisms dominate (Scheierling). These mechanisms include transfers of informal rights (such as farmer-to-farmer transfers), transfers made by legal means (such as when legislation establishes priorities at times of drought), transfers by formal administrative decisions (for example, by national, provincial/state, or basin entities), and informal transfers by stealth (for example, when expanding cities encroach on irrigated areas). While farmers are compensated in the case of water markets, and compensation may be paid in the case of administrative decisions (for example, if farmers giving up water supplies are readily identifiable and can bring political pressure to bear on decision makers), farmers are not usually paid in the case of transfers by stealth (although later complaints can trigger measures after the fact). Only limited information is available on many of these transfers and their effects—not just on water scarcity but also on efficiency and equity. Much could be done to shed more light on these reallocations and help improve them.

Measures for promoting and aligning private adaptation investments

While many of the adaptation investments will be carried out by the private sector, the private sector alone may not provide the desirable level of adaptation (for example, due to cost considerations). Private adaptation investments also focus on protecting and enhancing production systems and possibly supply lines and markets—they may not align with broader social objectives such as water conservation without public interventions, including incentives, coordination, and regulation (Chambwera and Heal; Noble and Huq).

One illustration is the conversion to more capital-intensive irrigation technologies. While farmers using groundwater to grow high-value crops may find it profitable to switch to drip irrigation, this may not be cost-effective for others. If public subsidies are to be provided to encourage further conversions in response to water scarcity, the objective(s) of such investments should be clearly stated. In addition, context-specific assessments should be carried out to avoid unintended or counterproductive outcomes with regard to irrigation water use—as well as uncompensated third party effects and related conflicts. In areas where return flows are important, care should be taken that farmers' consumption will (at least) not increase. A necessary, though not sufficient, rule should then be that the irrigated area not increase. In advanced water rights systems such as Colorado's, legal provisions specify the area to which an agricultural water right may be applied. Remote sensing via satellites can help enforce such rules. In areas without well-specified and enforced water rights, farmers should be informed if and to what extent reallocations are planned in connection with the subsidy program to allow them to adjust their practices accordingly.

More generally, care should be taken to ensure that a conversion program and the associated changes do not increase farmers' water-related (and other) risk exposures (OECD 2015a). A switch to more "efficient" irrigation technologies may provide incentives to farmers to follow a path toward more specialized production involving higher-value crops that may be more susceptible to a periodic lack of water, for example.

Improved groundwater management, not only in areas with deep or nonrenewable aquifers, will be necessary to make any significant progress with water conservation efforts in irrigated agriculture. In large parts of the world, groundwater irrigation remains largely uncoordinated and unregulated. In many instances, groundwater entitlements are linked with land property rights, which does not necessarily encourage water conservation or the consideration of externalities imposed on other aquifer users (OECD 2015b). If strong legal provisions exist, they often apply to irrigated areas with conjunctive water use and aim to prevent groundwater pumping from affecting stream flows and surface water rights or violating interstate water agreements (such as along the Platte River in eastern Colorado and Nebraska).

V. Going Forward

As water scarcity intensifies in many parts of the world, the need for adaptation investments from both private and public sectors in irrigated agriculture will increase. While engineering and technological adaptation measures are important, urgent progress will have to be made with policy and institutional adaptation measures. Such progress will include raising awareness on the severity of the water situation and its link to agricultural water use, but also on the complexities of designing adaptation measures for water resources compared to other resources or commodities. Progress will also require a much greater emphasis on research and development for fostering innovations not only in the traditional area of technologies, but in new policy and institutional arrangements to provide a framework for their effective implementation (Dinar).

Many adaptation measures in irrigated agriculture are currently not well explored, due in part to the lack of data on key water measures (including water withdrawn, applied, and consumed) and how they may change as a result of different interventions. An increasing number of studies are being carried out in advanced economies such as the United States, but due to the localized nature of many water problems, their insights are not readily transferrable to other situations. Since adaptation measures often need to be designed with the local context in mind, many more pre-implementation assessments should be carried out to estimate the costs and benefits and the associated risks of different investment options—incorporating, among other issues, hydrological aspects as well as the likely behavior of farmers and other affected parties. In addition, more emphasis should be given to post-implementation assessments that evaluate the implementation processes and results in line with the underlying objectives. These assessments would help inform decision makers in both the public and private sectors.

Adaptation investments related to irrigation water will increasingly have to take into account, and be integrated within, the wider policy framework, including in the agricultural and energy sectors. For example, subsidies that encourage crops with high water consumption may distort incentives for addressing water scarcity. Similarly, subsidies for cheap electricity or for solar-driven pumps may exacerbate groundwater exploitation.

As ever larger shares of total renewable water resources are being withdrawn and consumed for agricultural and other purposes—and as the level of interdependencies among users increases—even relatively minor shortfalls in water supplies may create unexpected economic, social, or environmental crises that currently applied adaptation measures will not be able to address. Planning for such events must attract increasing attention.

Endnotes

[1]Data from FAO (2016a) on agricultural water withdrawals include the annual quantities of water withdrawn for irrigation, livestock, and aquaculture purposes. Data from FAO (2016a) on total water withdrawals include the annual quantities of water withdrawn for agricultural, industrial, and municipal purposes. In-stream uses, such as recreation, navigation, and hydropower are not considered. Consumption, or evapotranspiration in the case of agriculture, is the amount of water actually depleted by the crops—that is, the amount of water lost to the atmosphere through evaporation from plant and soil surfaces and through transpiration by the plants, incorporated into plant products, or otherwise removed from the immediate water environment.

[2]Data from FAO (2016b) on the area equipped for irrigation include areas equipped for full and partial control irrigation, equipped lowland areas, pastures, and areas equipped for spate irrigation. They do not necessarily represent the area that is actually irrigated. The available data from FAO on the area actually irrigated are too limited for further analysis.

[3]Total renewable water resources comprise internal renewable water resources (specifically, the long-term average annual flow of rivers and recharge of aquifers generated from endogenous precipitation) and external renewable water resources (such as surface and groundwater inflows from upstream countries).

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Water Allocation in the West: Challenges and Opportunities

By Mike Young

When considering the role of water in an economy, it is useful to reflect on the "Diamond-Water Paradox" made famous by Adam Smith: "Nothing is more useful than water: but it will purchase scarcely anything; scarcely anything can be had in exchange for it. A diamond, on the contrary, has scarcely any use-value; but a very great quantity of other goods may frequently be had in exchange for it."

This paper explores the proposition that water management could be one of the U.S. economy's undiscovered jewels. It searches for opportunities to increase water's contribution to the economy without compromising environmental or social objectives.

Section I gives an overview of Australia's successful water reforms. Section II discusses water markets and allocations. Section III identifies 10 opportunities to improve water use in the United States. Section IV considers how the United States could proceed with water reform.

I. Water Reform in Australia

In 1986, when former Prime Minister Paul Keating was Australia's Treasurer, he famously said, "If this Government cannot get the

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adjustment, get manufacturing going again, and keep moderate wage outcomes and a sensible economic policy, then Australia is basically done for. We will end up being a third rate economy … a banana republic."[1]

At the time, Keating was worried about the significant number of government practices holding back opportunities for economic development and national prosperity. One of the practices that came to his attention was the way in which Australian states and territories managed water. Keating was worried that the systems used to manage water were acting as a barrier to economic progress.

If he were invited to the United States today and asked to review opportunities for improving this country's domestic economy, I am confident it would not take Keating long to suggest that it is time to look carefully at the management of water. Given the complex suite of arrangements in place, I also suspect it would not be long before he drew attention to the fact that the water right and management systems used in the United States evolved in a different era and in response to conditions that no longer exist. In the early 1990s, similar statements were being made about water management in Australia.

As prime minister, Keating went on to lead the implementation of a National Competition Policy that included a plan to transform water management throughout Australia. At the time, the Council of Australian Governments (comprising the prime minister, state premiers, territory chief ministers, and the head of local government) observed, "while progress is being made on a number of fronts to reform the water industry and to minimize unsustainable natural resource use, there currently exists within the water industry … impediments to irrigation water being transferred from low value broad-acre agriculture to higher value uses in horticulture, crop production and dairying."

Noting also that there was "widespread natural resource degradation which has an impact on the quality and/or quantity of the nation's water resources," the Council committed Australia to the "clarification of property rights, the allocation of water to the environment, the adoption of trading arrangements in water, institutional reform and public consultation and participation."

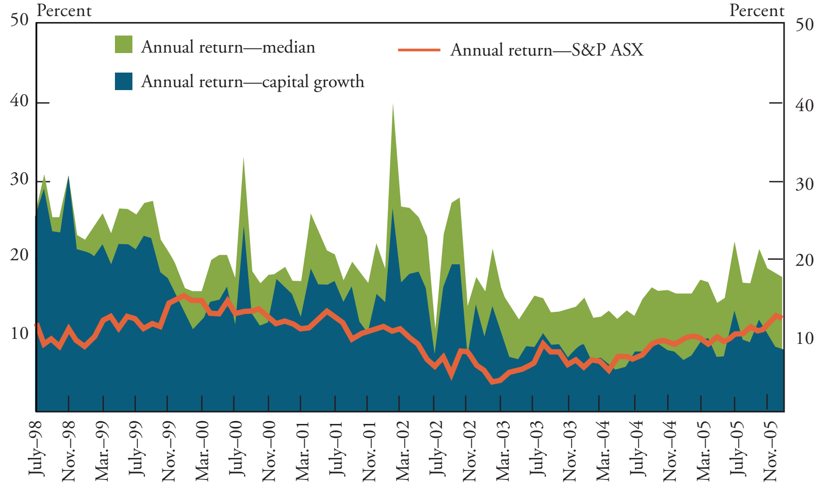
In the case of rural water services, the Council stated that the proposed new framework was "intended to generate the financial resources to maintain supply systems should users desire this and through a system of tradeable entitlements to allow water to flow to higher value uses subject to social, physical and environmental constraints. Where they have not already done so, States are to give priority to formally determining allocations or entitlements to water, including allocations for the environment."

Note that the emphasis in this statement is on determining water entitlements and allocations in a manner that enables markets to emerge. As a result, there has been a dramatic improvement in the economic efficiency of water use and, through this, significant innovation. The policy insight, which has yet to be grasped in the United States, is that if a nation is interested in using water-trading arrangements to manage scarcity and produce economic benefits, it should focus on transforming the constellation of legislative arrangements that have historically been the basis for managing water.

These initiatives were followed by a countrywide agreement to a National Water Initiative and then, following a change in government and the appointment of Australia's current prime minister, Malcolm Turnbull, as the minister for Water Resources, an agreement to prepare a new Murray-Darling Basin Plan and establish a new Murray-Darling Basin Authority. The National Water Initiative's roots lie in a commitment to ensuring water use makes the best contribution possible to the economy, revealing to all the costs of supplying and managing water and ensuring use is kept within sustainable limits. In the detail, one can find requirements to convert all water licences to perpetual or continuing shares, to meter use, and to facilitate low-cost trade including surface water trade across state borders. The Murray-Darling Basin Plan applies these same concepts by putting in place a small, independent six-member authority responsible for ensuring that the Murray-Darling Basin's surface and groundwater systems are managed as a single integrated system.

The agreements resulted in massive benefits for rural communities, for the economy, and for the environment. Among other things, the value of water rights in the Southern Connected River Murray System increased by well over 15 percent per year (Chart 1). In the United States, water reform is seen as a zero-sum game—in essence, a fight for a bigger share of the cake. The Australian experience would suggest, however, that it is possible to increase the contribution water makes to an economy and thereby make the cake much bigger.

Chart 1
Return from Reforming Water Rights



Notes: Chart shows return on investment from holding entitlement shares for five years, selling all allocations received during that period, and then selling the entitlement at the end of that period compared with returns achievable from holding a portfolio of Australian shares.
Source: After Bjornlund and Rossini.

Chart 1 only gives one perspective. Water reform increased gross regional domestic product during part of the last major drought by AUD 4.3 billion (2006–11) (NWC). Despite a greater than 70 percent decline in Murray-Darling Basin irrigated surface water, water trade possibilities meant that the adjusted gross value of irrigated production fell by just 10 percent (Kirby and others).

In addition to these economic benefits, water trading has resulted in positive environmental outcomes for the Murray-Darling Basin. The downstream trade of water during drought, for example, led to improved summer flow patterns and reduced system stress (Wheeler and others 2014). The development of water trading in Victoria produced a 20 EC reduction in the concentration of salt at Morgan at no cost to the government (Young, Shi, and Mcintyre).[2] Prior attempts to achieve the same outcome using expensive drainage schemes had only been able to achieve a 6 EC reduction. Surveys have found that water trading is now widely used by irrigators as a risk-management strategy (Zuo, Nauges, and Wheeler; Nauges, Wheeler, and Zuo).

II. Understanding Water Markets and Allocations

When water resources are scarce and facilitating reallocation is beneficial, governments face two options. They must either claw back water from existing users or allow users the opportunity to trade. Taking water back from existing users is politically difficult; hence, there is rising global interest in developing opportunities to trade.

When asked to talk about water markets and allocation arrangements, I normally start by pointing out the big difference between water markets and water trading. Markets typically involve many buyers and sellers all seeking to profit from ever-changing opportunities. However, few water systems are sufficiently connected and have storage capacities large enough to make establishing a true market possible. There are, however, many benefits from opening up opportunities to trade water entitlements and allocations.

The second observation I normally make is that two types of trading occur within well-defined water entitlement and allocation systems: allocation trading and entitlement trading.

In allocation trading, allocations normally take the form of a specific volume of water that may be taken from a system within a nominated period of time. In entitlement trading, entitlements need to be defined unambiguously and, if efficient investment is the goal, are best defined as a perpetual entitlement to a share of all allocations made (Young 2014).

In Australia, these two different forms of trading are often called temporary and permanent trading. They are possible, however, only when the entitlement, allocation, and use management systems are fully unbundled and the governance, accounting, and enforcement systems that surround them are robust. When robust water allocation arrangements are missing, water users are reluctant to invest and governments are forced to revert to less efficient ways to influence water use. In Australia, the leasing of water rights is rare and fallowing agreements unheard of because it is so easy to trade allocations. In much of the United States, however, there is no metering of water use and, hence, these inefficient practices are common.

The third observation I normally make is that the Australian experience suggests that rather than focusing on the development of water markets, greater progress will be made if the focus is on establishing a suite of institutional conditions that make it possible for water entitlements and allocations to be traded at low cost. When institutional conditions create a sense of confidence, water users will seek opportunities to trade water entitlements and allocations whenever it is possible to gain from doing so. When the costs of trade or the institutional risks are high, they will seek other ways to make money.

Fourthly, I think it is important to focus on the narratives we employ when discussing opportunities to improve the way water is allocated and used. Many debates in the United States are presented as an argument about the need to recut that cake. But when the narrative is framed as a cake-cutting exercise, stakeholders tend to spend an inordinate amount of time fighting in an attempt to make sure their share of the cake is protected. The alternative narrative focuses on finding a way to grow the cake and make everyone better off. Win-win solutions become possible. Presentations that start by searching for ways to increase the contribution water can make to the economy, to communities, and to the environment are much more likely to gain stakeholder interest. Irrigators are likely to be less fearful of change if the discussion begins by focusing on ways to improve the value of the opportunities available to them.

Fifthly, words also matter. In this paper, the term "water right" is used cautiously. Discussions about transitioning to a new system become easier when the language used is new and no term has an old meaning. Early in Australia's water reform process, those responsible for ensuring the process worked developed a new glossary of terms.[3] Discussions about rights were replaced with discussions about access to entitlements, shares, and allocations.

III. Opportunities to Improve Water Use in the United States

Water trading in a variety of forms is well-established in some parts of the United States and is expanding. Even though impressive progress is being made in some water management districts, overall progress is patchy. Reports summarizing the extent of overuse, resource depletion, and inefficient use are common. To facilitate a transition to more sustainable and efficient practices, the Western State Governors Association (2012) has recommended the increased use of water market and trading arrangements but has not yet come up with guidelines to achieve this goal.

To catalyze interest in building upon the Australian experience, last year, the Nicholas Institute developed a blueprint for water reform in the western United States (Young 2015). This blueprint builds upon a more generalized framework for the design of robust water abstraction regimes and seeks to assist U.S. water managers in avoiding Australia's many water reform mistakes by identifying their solutions. Box 1 summarizes the results as a set of lessons. Box 2 contains an Organisation for Economic Co-operation and Development (OECD) checklist designed to enable anyone to assess the health of their water entitlement, allocation, and management regime.

The search for opportunities to improve water entitlement, allocation, and sharing systems is context-specific. As a result, it is difficult to write about in a way that will seem relevant to all. However, four concepts do seem to prevail. These are the benefits of unbundling, improving, and validating existing water rights; the benefits of establishing robust water resource plans; the benefits of transitioning toward decision-making structures characterized by trust, efficiency, and rigorous enforcement; and the merits of assigning water entitlements to the environment.

These broad concepts, however, hide many of the opportunities to reduce risk and ensure that water everywhere is put to best use. In the remainder of this paper, I wish to draw attention to 10 opportunities worthy of consideration by those interested in improving water's contribution to the U.S. economy, to community development, and to the environment. It is stressed that markets are very good at recognizing the extent of risk and the lack of certainty. As risks increase, asset values decrease.

Opportunity one: establish centralized water-right registers

An outsider might expect that when state laws are used to create and issue water rights, discovering who holds these rights and what the holders of these rights are allowed to do would be relatively easy. Throughout much of the United States, however, there is considerable uncertainty as to which people hold which rights, even in regions where the water resource has been adjudicated. This uncertainty can arise when rights are either defined by statute but not documented or defined using a paper trail that is complex and not well maintained.

Box 1

Lessons from the Australian Experience in the Development of Water Trading and Marketing Arrangements

Lesson 1. Unless carefully managed, the legacy of prior licensing decisions can result in markets causing overallocation problems that erode the health of rivers, aquifers, and the water-dependent ecosystems associated with them.

Lesson 2. Transaction and administrative costs are lower when entitlements are defined using a unit share structure and not as an entitlement to a volume of water.

Lesson 3. Market efficiency is improved by using separate structures to define entitlements, manage allocations, and control water use.

Lesson 4. Early attention to the development of accurate license registers is critical and a necessary precondition to the developing low-cost entitlement trading systems.

Lesson 5. Unless water market and allocation procedures allow unused water to be carried forward from year to year, trading may increase the severity of droughts.

Lesson 6. Early installation of meters and conversion from area-based licenses to a volumetric management system are necessary precursors to developing low-cost allocation trading systems.

Lesson 7. It is difficult for communities to plan for an adverse climate shift and develop water sharing plans that deal adequately with a climatic shift to a drier regime. Robust planning and water entitlement systems that facilitate autonomous adjustment are needed.

Lesson 8. The allocation regime for the provision of water necessary to maintain minimum flows, provide for conveyance, and cover evaporative losses needs to be more secure than that used to allocate water for environmental and other purposes.

Lesson 9. Unless all forms of water use are accounted for, entitlement reliability will be eroded by the expansion of unmetered uses, such as plantation forestry, farm dam development, and increases in irrigation efficiency.

Lesson 10. Unless connected ground and surface water systems are managed as a single integrated resource, groundwater development will reduce the amount of water available to allocate to surface water users.

Lesson 11. Water use and investment will be more efficient if all users are exposed to at least the full lower bound cost and preferably the upper bound cost of supplying their water. One way of achieving this outcome is transferring ownership of the supply system to these users.

Lesson 12. Managing environmental externalities using separate instruments is important to ensure the costs of creating externalities are reflected in production costs and to provide an incentive to avoid incurring these costs.

Lesson 13. Removing administrative impediments to interregional and interstate trade is difficult but necessary for the development of efficient water markets.

Lesson 14. Markets will be more efficient and the volume of trade will increase if entitlements are allocated to individual users rather than to irrigator-controlled water supply companies and cooperatives.

Lesson 15. Equity and fairness principles require disciplined governance so that all people have equal access and opportunity to profit from allocation decisions and policy announcements.

Lesson 16. Water markets are more effective when information about the prices being paid and offered is made available to all participants in a timely manner.

Lesson 17. Developing a brokering industry can avoid government involvement in the provision of water broking services.

Lesson 18. When introducing a new policy framework, adopting a suite of new terms is helpful so that differences between new and old concepts are easily understood.

Sources: Adapted from Young (2010) and Young and Esau.

Box 2

A Checklist for Assessing the Capacity of a Water Resource Entitlement, Allocation, and Management Regime

Check 1. Are there accountability mechanisms in place for the management of water allocation that are effective at a catchment or basin scale?

Check 2. Is there a clear legal status for all water resources (surface and ground water and alternative sources of supply)?

Check 3. Is the availability of water resources (surface water, groundwater, and alternative sources of supply) and possible scarcity well-understood?

Check 4. Is there an abstraction limit ("cap") that reflects on-site requirements and sustainable use?

Check 5. Is there an effective approach to fairly and efficiently manage the risk of shortage that ensures water for essential uses?

Check 6. Are adequate arrangements in place for dealing with exceptional circumstances (such as drought or severe pollution events)?

Check 7. Is there a process for dealing with new entrants and for increasing or varying existing entitlements?

Check 8. Are there effective mechanisms for monitoring and enforcement with clear and legally robust sanctions?

Check 9. Are water infrastructures in place to store, treat, and deliver water in order for the allocation regime to function effectively?

Check 10. Is there policy coherence across sectors that affect water resources allocation?

Check 11. Is there a clear legal definition of water entitlements?

Check 12. Are appropriate abstraction charges in place for all users that reflect the abstraction's effect on resource availability for other users and the environment?

Check 13. Are obligations related to return flows and discharges properly specified and enforced?

Check 14. Does the system allow water users to reallocate water among themselves to improve the allocative efficiency of the regime?

Source: OECD drawing upon Young (2013).

As a result, it is difficult in most states—if not all—to discover who owns what, let alone manage properly what states believe they have on record. Given this difficulty, the first opportunity to improve water management in the United States is to offer all water right holders the opportunity to convert their existing water right into a "new" water right recorded on a central register of guaranteed integrity. Building on well-established Torrens Title record-keeping principles, legislation should provide that the only way a person can own a "new" water right is by having their name recorded on the new state water register (Young and McColl).[4]

When rights are recorded on a central register of guaranteed integrity, it becomes possible to trade these rights at very low cost and minimal legal risk. As a result, the value of new system rights tends to be significantly greater than the value of the old system rights they replace. The value of these new water rights can be increased further by making it possible to register a financial interest in these rights and by guaranteeing to only allow their sale with the consent of all registered mortgagees.

Note that the process to establish such a new right requires only that the old right be validated. It does not require a full U.S.-style adjudication process. During the Australian water reform process, described above, all states established new water entitlement registers. As a result, banks became much more interested in funding investment in new water technology. On average, the validation of a New South Wales water right required only about one person-hour per water user (Young and Esau).

Moreover, the above process can be presented as a process of conversion and validation of existing rights designed to reduce legal risk and, thereby, increase opportunities to trade. Care needs to be taken to ensure conversion is not seen as an underhanded way to extinguish existing rights. The process need not be threatening and can be commenced independently of a decision to pursue a broader water reform agenda.

Opportunity two: unbundle water entitlement, allocation, and use management

During the process of reforming water management in Australia, nearly all water "licenses" were partitioned into their component parts in a manner that enabled each component to be managed separately. The result significantly reduced administrative costs and, as entitlements and allocations become fungible, increased opportunities to trade.

Unbundled water entitlement and allocation arrangements borrow administrative structures and processes used by corporations to define ownership, by banks to track deposits and withdrawals, and by the Federal Open Market Committee to increase confidence in the U.S. economy. Applied to water, these concepts suggest that water rights should be defined as shares so that it is clear that no allocation can be guaranteed; that allocations should be made via a formal announcement in the same manner as dividend announcements are made; that allocations should be made by crediting each shareholder's water account; and that all site-specific water-use conditions should be moved to a separate permit.

The result is a structure that makes it clear that all water supply systems involve risks that have to be managed. The best that can be offered is a guarantee to a share of allocations made and, where necessary, the establishment of share classes of high and low reliability. Low-cost transactions can then be achieved by establishing banklike accounting systems and formal announcement systems similar to those used in the corporate world to announce and pay dividends. Transaction costs are kept low by making both shares and allocations as fungible as possible. In practice, this is achieved by separating location-specific use controls from the systems used to track share ownership and the volumes of water that may be taken from a water resource.

The third part of the unbundling process—a separate policy instrument to control use—requires issuing a permit that nominates the water account from which to deduct use, states how water use will be measured, and stipulates the conditions under which water may be used at a specific location.

The last of these requirements is particularly important. In many parts of the United States, if a water entitlement is not put to a beneficial use, the entitlement is at risk of curtailment. In an unbundled structure, beneficial use conditions only kick in when water is taken from a resource. That is, there is no obligation to "use" a water entitlement or to use water in a water account. Use approvals operate like a development approval and allow the efficient management of third-party objections to a proposed change in water use. In an unbundled water entitlement and allocation system, there is no beneficial obligation to use every drop of water allocated. The result is a structure that gives each and every water account holder an economic incentive to save water.

Unbundling has one further benefit of immense importance to the improvement of water management in the United States. In an unbundled regime, third-party effects are managed through the conditions in a use approval and in water resource management plans. If a person is concerned about the likely effects of water use at a location near or upstream of them, then they may seek to stop the use approval or change an exchange rate. They cannot, however, stop allocations being made or transferred from one account to another. The result is an arrangement that, in particular, requires third parties to pay attention to the decision-making rules set out in water resource management plans.

At the same time, unbundling opens up opportunities for more efficient investment. An aspiring almond grower, for example, can secure all the development and water use approvals without having to secure a drop of water. This can be left until it is time to secure the water needed and done as fast as the almond trees grow. The result ensures much more efficient use of capital in irrigation.

Note also that in fully unbundled water entitlement and allocation systems, robust management planning processes are used to determine how much water can be allocated to shareholders. As in the corporate world, water—like dividends—is never allocated until managers are confident they can make the allocation.

Opportunity three: statutory water resource plans

In 2014, California passed legislation requiring the appointment of groundwater sustainability agencies which, once appointed, will be required to prepare plans for the "sustainable" management of the groundwater resources these agencies' boundaries overlie. The legislation also permits these agencies to specifically regulate, limit, and suspend groundwater extractions to achieve the sustainability goals put forth in the agencies' plans. This opens up the opportunity to improve the way opportunities to use groundwater are defined, allocated, and managed. Nevada has similar legislation that authorizes its state engineer to require the preparation of a management plan for any water resources that is in a critical state.

The first question that needs to be asked is what form should each of these plans take? If the aim is to increase the contribution water resource plans make to an economy and establish ground rules for water allocation, then these plans should be drafted in a manner that reduces the potential for legal argument. This can be achieved by making it clear that the rules in the plan are binding and may be changed only through due public process.

The robustness of these management plans can be strengthened further by drafting them in a manner that resembles a decision-making guide and deliberately leaving out detailed descriptions of the resource and the reasons why decisions have been made. By way of example, it is better to legislate a 0.9 exchange rate for the transfer of water allocations from location A to location B than to legislate that such transfers occur only in a manner that has no adverse effects on third parties. Many parts of the United States take the opposite approach; as a consequence, many attempts to transfer water end up in extremely expensive court cases, and many transfers are never contemplated.

In Australia, the risk of legal challenges is minimized further by making water resource plans statutory. That is, each local agency's water resource plan is presented to the legislature for final approval and thereby gains the same legal standing as any other approved legislation. The result is a framework that makes it possible for local boards and water masters to make allocation decisions as quickly as water supply conditions change. Confidence in the constellation of administrative arrangements used is such that an allocation trade can be completed in the Murray-Darling Basin without any legal risk in 40 minutes.[5] In addition, as the costs of a trade are low, trading is common and routinely contemplated by all irrigators. Trading occurs in the United States, but as the costs are so high and the legal risks considerable, only large-scale farmers tend to contemplate trades. Water use would be much more efficient if all irrigators, including those with relatively small farms, were exposed to processes that reveal the marginal opportunity cost of water use.

Plans also need to avoid concepts that are scientifically contestable and be devoid of complex assessment of climatic risk. As a result of interest in the Blueprint we have developed, the Diamond Valley community in Nevada is considering basing its allocation decisions upon changes in the average depth to groundwater at four wells. If the average depth to groundwater declines, allocations per share in the following year should be reduced by between 2 percent and 6 percent. Simple rules like this are much easier to explain and much harder to contest in a court of law than decision-making approaches that rely upon complex models.

Opportunity four: replace prior appropriation with a small number of security pools

Figure 1 sets out a generic framework for developing a robust water-sharing arrangement to allow the efficient use of water. In practice, base flows and floodwaters are managed under management rules and the rest according to priority-sharing rules.

In many western U.S. water allocation systems, rights are defined using a prior appropriation arrangement that gives each water right priority according to the date on which a holder's right was issued. This means that every water right is unique in terms of its seniority and has a different value. For surface water systems, the alternative approach used in Australia is to establish several security pools and issue shares in each pool.

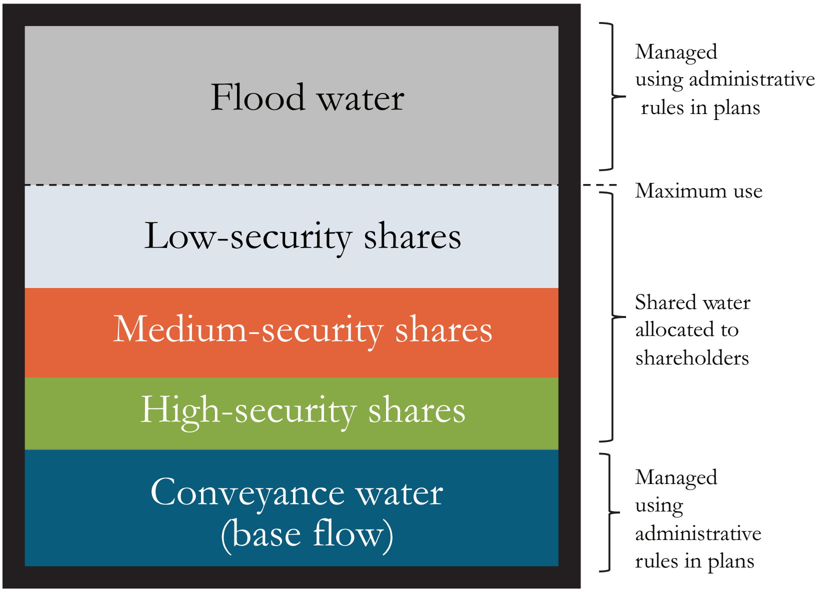
When several security pools are established, allocations are made to the high-security pool until its maximum allocation volume is reached. Allocations are then made to the general security pool and finally to the most junior, low security, pool.

When several sharing pools are in place, the resulting structure enables both the efficient management of supply risk and, because of the fungibility of shares, efficient price discovery. Moreover, because each share is identical, third parties cannot object to a sale of shares from one person to another. Note also that as supplies become scarcer, the value of high-security shares can be expected to increase.

In passing, it is worth noting that a specialist in the design of such regimes will recommend that the maximum size of each pool be defined using a moving average of all allocations made, so that if a long dry period emerges, the fact that it is getting wetter or drier is signaled to all water users.

Figure 1

Developing a Water-Sharing Arrangement that Enables Efficient Risk Management



Statutory plans and the legislation authorizing their preparation can be used to assign responsibility for managing risks in a transparent manner. Under Australia's National Water Initiative, for example, full responsibility for adapting to climatic variability and change is assigned to shareholders, while responsibility for managing changes in environmental preference are assigned to the government acting on behalf of society.

Opportunity five: giving the environment an entitlement

More by accident than good design, Australia has discovered the benefits of a sophisticated approach to the pursuit of what are often described as environmental objectives. This came about because the government decided to restore some systems to environmental health by purchasing water entitlements for the environment from willing sellers. When the federal government began purchasing water entitlements (shares) for the environment, Treasury officials were not prepared to surrender this new asset. As a result, the shares so purchased came to be held in trust for the environment.

Assigning water rights to the environment, rather than treating it as something to be awkwardly managed through complex administrative processes, has produced many benefits. First and foremost, the environment as a shareholder receives allocations in the same way as all other shareholders. In the past, overuse and overallocation led to significant degradation of water-dependent ecosystems. Under the new regime, the environment—just like all other shareholders—receives an allocation every time allocations are made. The trustees appointed to manage these allocations have to decide what to do with them. As a result, environmental water use has become more efficient, and a new cadre of environmental water managers has emerged. Instead of spending their time trying to influence others, these new managers are much more interested in maximizing environmental benefits per acre-foot of water made available to them.

In the past, those interested in the environment never considered the need for efficiency in the way they manage water assigned to the environment. Now, they do. Along the way, these managers discovered the benefits of countercyclical trading. Countercyclical trading involves the environmental trustees selling environmental water allocations to irrigators during a drought, then using the revenue received to purchase more shares or fund investments in environmental infrastructure.

Opportunity six: trusted governance

Transitioning from an old to a new water management regime requires consultation and administrative processes that gain community trust, especially when the prior regime was dysfunctional. When searching for ways to build trust, there is tension between the desires for a representative versus an expertise-based governance. Tensions also exist between top-down centralist approaches and bottom-up local approaches. Finally, there is a need to ensure adequate and full engagement.

From a market perspective, one other consideration needs to be put on the table. In any situation where a market operates and information about the state of the resource and likely future decisions are privileged, insider trading risks have to be managed. As a result, there is a strong case for assigning responsibility for the development, implementation, and enforcement of water resource plans to expertise-based boards and limiting representative governance processes to the appointment of board directors. As is the case in the corporate world, if shareholders are appointed to such a board, they should not be able to trade in the same manner as any other shareholder. The Nicholas Institute Blueprint recommends that western states in the United States consider appointing small, expertise-based boards who are responsible for developing and managing a water resource on the condition that they consider the advice of appropriately constructed stakeholder reference panels. If shareholders are appointed to a board and have either a direct or indirect interest in water shares, then they should not be allowed to trade when allocation decisions are being made or policies are under review.

If robust water trading and marketing arrangements are to become the norm in the United States, then those tasked with their implementation must be trusted. When trust declines, as is the case in the corporate world, the composition of the board must change quickly. Among other things, it is critical that board decisions are supported publicly by all of its members. If a member, having been involved in a decision, wishes to express public dissatisfaction with that decision, then that member should resign. Otherwise, a board should be seen to be unanimously making decisions in the best interests of all shareholders as guided by the rules set out in the agency's water resource management plan.

Opportunity seven: nested planning hierarchies

One of the more serious mistakes Australia made as it began its water reform program was focusing on surface water systems and not bringing groundwater systems into the same process. Several U.S. states appear to be making the same mistake. The obvious solution to managing connections between water resources is bringing them together under one integrated management system.

In large systems, typically a high-level basin plan or its equivalent requires establishing a separate authority. Under these "basin plans," allocations are made to each defined ground or surface water resource and then distributed to shareholders by the decision making board or manager responsible for the day-to-day implementation of that resource.

Note that for efficient management, allocations need to be managed on a resource-by-resource basis in a "nested" manner that allows individual users to transfer water allocations between, for example, ground and surface water systems. When this is done, shareholders have an incentive to invest in groundwater storage, carry forward unused water allocations from year to year, and generally optimize the management of stocks and flows.

Australian experience suggests that as knowledge about system interconnectivity tends to be imperfect, a considerable degree of pragmatism is required. Recognizing that it is better to be approximately right rather than comprehensively wrong, initial plans need to set limits on the amount that can be taken from each resource and develop system-wide accounting systems that can be improved. One of the more difficult decisions, which requires a considerable degree of pragmatism, is setting transmission exchange rates in unregulated streams developing effective ways to shepherd water from one river reach to another. Determining the amount of water to be set aside to prevent seawater intrusion is another consideration. Solutions to each of these problems are known, but this paper is not the place to discuss them.

With such structures in place, surface water users can be given credit for transferring surface water to a groundwater system and vice-versa by setting and periodically revising exchange rates and storage loss adjustments as knowledge improves. The result increases the value of shares in both resources and builds resilience.

Decisions about how many water resource plans to prepare are context-specific and need to be made carefully. Australia has a single plan for all the ground and surface water resources in the Murray-Darling Basin and a suite of regional plans for each ground and surface water resource. Most groundwater resources and most surface water resources are zoned. As a guiding rule, shares are issued on a zone-by-zone basis.

Opportunity eight: simplification by adopting gross rather than net water accounting regimes

When water use is inefficient, a considerable portion of the water taken from an aquifer, for example, drains back through the soil and ultimately becomes available for use by someone else or makes a contribution to the environment. Known as return flows, this biophysical reality has to be managed. Otherwise, as water use efficiency (in a technical sense) increases, the amount of water that returns to the system decreases, and there is a total increase in water consumption.

Conceptually, there are two ways to manage the return flow issue. The first option is to run a net accounting regime, as is done in much of the United States, and require changes in water-use efficiency to be accounted for on a case-by-case basis. The result, however, is administratively expensive. The second option, commonly used in Australia, is to run a gross accounting system and commit to a regime that reduces allocations per share as the average efficiency of irrigation increases. Both approaches have hydrological integrity. When a gross accounting system is introduced, however, transaction costs are much lower, as there is no need to track land use and make adjustments to water accounts at the individual level.

As a general rule, the value of water entitlements will be greater under a gross water accounting regime, as transaction costs will be less. In some cases, a mixed accounting system may be appropriate, especially when there are strong connections between ground and surface water resources and some users consume 100 percent of the water they take while others return a significant volume. One of the more common examples of a water user who uses 100 percent of the water allocated to them is someone who pumps the water they use out of a basin. A flood irrigator, on the other hand, may only consume 50 percent of the water they pump from a water resource. In practice, the challenge is keeping the accounting system simple and affordable. Again, it is better to be approximately right than comprehensively wrong.

Note also that technology is changing. It is likely that in some regions and for some types of water use, it may soon be cheaper to account for net water use via satellite imagery than to rely upon data taken from flow meters and assumptions about return flow.

Opportunity nine: tagged entitlement trading

When water users seek to transfer water from one region to another, the transaction can be completed either by surrendering the entitlement in one water district and issuing a new entitlement in another district or by allowing the purchaser to "tag" an entitlement with a guarantee that any allocation made to this entitlement will be transferred automatically to another region at the current exchange rate.

In Australia, the latter approach is known as a tagged trade and has become popular as it assigns 100 percent of the exchange rate risk to the buyer and enables downstream users to reduce supply risk by holding entitlements in different parts of a river system. Tagged trading increases the value of entitlements in areas that are climatically different. Value is increased further by developing a process that reduces transaction costs and risks to third parties. Under this arrangement, third-party effects are managed by revising exchange rates as knowledge about the nature of flows and connectivity improves. As noted earlier, however, investment confidence should be such that in the long run, there is no need to apply for a guarantee that a governance regime will not reverse a decision to allow the transfer of water between regions or set capricious conditions on such transfers.

Opportunity 10: allocating rights to individual users

In many parts of the United States, as was the case in Australia, water users are encouraged to trade water allocations and entitlements within a district. Deals to trade water between districts, however, tend to be negotiated by district managers and allowed only when it does not threaten the viability of the district as a whole. This discourages district managers from continuously improving the way they manage their system. The alternative approach, used in Australia, is to allocate water entitlements to individual irrigators and require all districts to allow both the permanent and temporary trade of water out of their districts.

If applied without considering the effect of such an arrangement on the costs of an operating district's infrastructure, this approach could discourage the efficient management of water supply and delivery arrangements. To remove this disincentive, Australian districts are allowed to charge a termination or exit fee. At present, the maximum fee is set at 10 times the annual fixed charge per water share (ACCC 2008). The result is an arrangement that forces inefficiently-managed districts to review the efficiency of their operations and search for more efficient ways to provide water to their customers.[6]

IV. Toward Improved Water Allocation and Management

The preceding set of 10 opportunities to improve institutional arrangements used to manage water in the United States is far from comprehensive. Moreover, efforts are already underway to put many of them in place. Water trading is not new to the United States. In some regions, transition to full implementation of the type of regime outlined above is relatively simple. In others, transition may be more protracted and cannot be implemented by simply tweaking one or two features.

As a well-known Australian land administrator, Sir William Payne, said in 1960, "new precedents are waiting to be born." If a paper like this were written at the time he wrote these words, almost everyone would have thought it impossible to transition to the water management regimes now used throughout Australia. With the benefit of hindsight, it has been demonstrated that transformation is possible. I think that the time has come for the United States to consider investing in the processes that would enable it to make such a transition but to do so in a manner that does not repeat Australia's many mistakes.

One way to start would be to enable the establishment of water right registers in a manner that enables seasonal allocations to be made and then build water accounts that record precisely the number of allocations that each user has not yet used. The latter requires metering or its satellite-based equivalent and developing robust governance arrangements. Such a transition need not come from a top-down decree at a state or national level. In most states, however, the transition will be easier if enabling legislation is put in place. As stated earlier, the arguments can be built around the economic benefits, not the need for greater control.

Arguably, transition is easier in water districts and regions in a critical condition. Transition will be easier, too, in states where the administrative leadership has the experience, understanding, and capacity to assist district leaders and water resource managers in transitioning to a new regime with minimal controversy. As set out in the Nicholas Institute Blueprint, one option is to begin with a number of pilots that demonstrate it is possible to convert from a "first-in-time, first-in-right" water management regime to a robust water-sharing regime.

Irrigators in Nevada's Diamond Valley are already pioneering this journey. Other water resources are now searching for a similar opportunity. In particular, and as a result of the Sustainable Groundwater Management Act, several of California's groundwater management districts have shown interest in pursuing the first-mover opportunity that will pass to those committed to finding a new way to manage their water resources so as to maximize opportunity and minimize risk.

The conversion of land and water titles from an old to a new system suggests that old and new systems can be run side by side with one another. One option is to assign responsibility for the setting up of new water entitlement registers to Land Title Offices.

At the national level, an outsider may be tempted to observe that too much attention is being given to stressed water resources. There is a strong case for moving ahead of the game and acting before problems emerge. The return on investment from moving ahead of the game and avoiding the very high costs of having to resolve overallocation problems could be substantial.

A recent report for the governments of England and Wales suggests that all water resources should be closed when permitted use reaches 70 percent of potential (Young 2012). Upon closure, 70 percent of all the shares to be issued would be allocated to existing users and the remaining 30 percent issued to the government. It would then be up to the government of the day to decide how many of the remaining shares to issue to the environment, how many to hold in reserve, how many to give away, and how many to auction.

A role for the U.S. federal government?

Is there a case for federal involvement in water reform? The economic case for encouraging U.S. states to transition to the development of robust water-sharing arrangements is strong, especially when the cost to society of ongoing mismanagement and litigation is considered. It also needs to be recognized that reform takes time. While Australia started its water-reform journey in the 1990s, the full repair of the Murray-Darling System is not expected before 2023. Learning from the Australian experience may enable the United States to move faster, but it should also expect the process to take at least 20 years.

The first federal opportunity I can identify is to make money available to assist districts willing to pilot test and demonstrate the benefits of moving to robust water-management arrangements. Early investments could include paying for the costs of developing new water registers, new water accounting systems, and installing smart water meters that link to water accounts. Federal involvement might enable the development of systems that work efficiently across state borders.

The second federal opportunity is to search for efficient ways to pass the governance of overlapping federal and state interests in water to single, integrated management systems. Ultimately, the U.S. economy will be best served if a way can be found to rely upon robust water resource management plans and water-sharing systems to determine how much and where water is consumed. As a demonstration of good faith in areas where pilot-testing is occurring and about to occur, federal government agencies could, for example, show willingness to convert their rights into shares, agree to work under the conditions set out in water resource management plans, and accept decisions made by an independent expertise-based board.

A third, more sensitive, opportunity is to show willingness to enable the efficient management of environmental considerations such as endangered species. In an ideal world and in regions where a water resource management plan has been approved by a state, it should not be possible for a court to do more than order the review of a management plan. This process could be facilitated through federal government involvement in the purchase and management of water rights for the environment. In Australia, it is now expected that the Commonwealth Environmental Water Holder, acting on behalf of all, will end up holding well in excess of 20 percent of shares in the Murray-Darling Basin Plan system. Imagine what would happen if a similar structure existed in the Colorado River System and if environmental water users were free to move water among states on a daily basis.

Costs and benefits

As far as I am aware, no cost-benefit analysis of the merits of resolving many water-related environmental challenges facing the United States has been conducted. In the process of preparing the Murray-Darling Basin Plan, several such analyses were conducted; they played an important role in convincing Australia's political leadership to support this transition. The effects of the Millennium Drought, the merits of validating registers, and an understanding of the merits of building an institutional structure that enables rapid, low-cost water trading across state boundaries led to bipartisan support. As a result, Australia has much experience to share.

Assessing the merits of shifting to a new, robust water resource sharing arrangement requires models that can test policy alternatives. Wittwer (2015), for example, converts a computable general-equilibrium model for Australia into a model that can track the regional implications of severe drought in California's Central Valley under a drought scenario requiring a 40 percent cut in water availability. Under the current administrative regime, the value of farm output is reduced by 10 to 20 percent. Under unfettered Australian-style allocation trading conditions, farm output is reduced without water trading after accounting for substitution away from water. In this scenario, farm output in the Central Valley drops by only 5.4 percent. That is, transition to a regime consistent with the framework suggested in this paper might halve the effect of a drought and do so without adversely affecting groundwater supplies.

In Nevada, the state engineer has declared the Diamond Valley Groundwater resource to be in a critical state. As a result, in 10 years, he must curtail the use of all water rights issued after 1960. Most farms hold a mixture of pre-1960 "senior" and post-1960 "junior" rights, a few farms only hold "senior" pre-1960 rights, and a few only hold "junior" post-1960 rights. It is our expectation that moving to a sharing systems is likely to produce significant economic benefits and also significant social benefits to the community that, as a result of conversion, does not become embroiled in an ugly political and legal fight.

Much more analysis of the merits of improving the water entitlement, allocation, and management arrangements in the United States is needed. The benefits of moving to more robust water management regimes are likely to be substantial in terms of avoiding the adverse costs of ongoing mismanagement and also in terms of the increased economic and environmental benefits.

At the highest level, the majority of the gains will come from transitioning to a relatively simple regime devoid of the many legal and administrative arrangements that so often impede progress or make it unbearably costly. With these arrangements in place, speedy, low-cost trading will become possible; investment and innovation will significantly increase; and known environmental challenges will be resolved at much less cost than otherwise would be the case.

Endnotes

[1]Speaking to John Laws on Radio 2UE, May 14, 1986.

[2] Electrical conductivity, or EC, is the standard measure of water quality.

[3]The blueprint contains a draft list for consideration by those interested in improving U.S. water policy.

[4]The Torrens Title system operates on the principle of "title by registration" (granting the high indefeasibility of a registered ownership) rather than "registration of title." The system does away with the need for proving a chain of title (specifically, tracing title through a series of documents). The state guarantees title and is usually supported by a compensation scheme for those who lose their title due to private fraud or error in the state's operation. For more information, see *https://en.wikipedia.org/wiki/Torrens_title.*

[5] Tom Rooney (Waterfind Australia) in an email to the author September 2016.

[6]In Australia, when this arrangement was introduced and as a transitional arrangement, one state was allowed to set a 10 percent limit on the permanent transfer of water shares out of a district so that there was time to reconfigure delivery infrastructure and generally improve service delivery.

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Conference Themes and Policy Responses

By Richard Howitt

The central theme that emerged in the conference papers was of the growing scarcity of water, both physical and economic, coupled with increasing uncertainty about how and where this water scarcity will affect society. The uncertainty of future water demands and supplies is nonstationary and ever-changing due to the effects of climate change, which will accelerate during the first half of the century.

Five main factors are driving increased water scarcity on both the demand and supply side: increased food demand driven by population growth, increased demand for animal protein in developing economies, reductions in water supply as some critical groundwater basins are forced into stabilization, changes in the intensity and location of precipitation due to climate change, and changes in the ability to store seasonal water due to increased ambient temperature.[1]

Adaptation mechanisms to respond to this increased scarcity include agricultural productivity growth, changes in irrigation technologies, changes in water allocation institutions such as markets, narrowing the yield gap on food crops, and providing cheap and improved information with which to manage water.

Section I summarizes conference papers that address alternative adaptation approaches to water scarcity. Section II discusses papers that

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reviewed the potential for technological and institutional solutions to water scarcity. Section III discusses three topics that were not deeply addressed in the conference—namely, the application of community-level endogenous institutions for water management, the importance of maintaining water quality for domestic use and agriculture, and the potential effect of emerging methods for remotely measuring resource information for water management in both developing and developed agricultural economies.

I. Adaptation to Water Scarcity

Susanne M. Scheierling and David O. Treguer's paper develops a global perspective of water scarcity which they measure as the difference between total withdrawals and total renewable flows. Their data show that in many basins, agricultural withdrawals alone are already larger than total renewables. Scheierling and Treguer show that when measuring water scarcity as withdrawals as a percent of total renewable water, resource scarcity varies from over 100 percent in the Middle East and North Africa to as low as 10 percent in several other regions. Kenneth G. Cassman also raises the problem of persistent overdraft in several major aquifers. He notes that much of the overdraft is due to poor governance institutions, but even with good governance, the overall extraction rate will have to be reduced. In contrast, in many parts of Africa and some parts of Latin America, there seem to be opportunities to expand irrigation well use and efficiency. Cassman concludes the current global irrigated area can be maintained but is unlikely to be increased.

Bonnie G. Colby's paper also addresses the difficulties of establishing efficient institutions on a national and international scale when there are significant linkages with other important sectors of the economy such as energy, municipal and industrial use, and environmental values. She shows how consumption by these different sectors differs significantly across regions of the United States. She cites some situations in which traditional community values are at odds with market signals, probably due to incomplete definition of the property rights to the resource. She concludes with a review of water trading that shows it to be a robust scarcity adaptation and shows how the quantities traded in Colorado River basin states changed from 1987 to 2010.

Several authors note a lack of consistent data on net water use and the value of water productivity. The data showing the dominance of India and China in irrigated water use and area implicitly draw attention to the importance of the sustainable groundwater extraction in both of these regions. In contrast, in her comments on the paper by Scheierling and Treguer, Quiqiong Huang stated that unsustainable groundwater use was concentrated in certain parts of northeast China, while other regions were essentially using groundwater in a sustainable manner.

Despite the concern from several conference participants (Rosegrant, Scheierling, Cassman, Gruere, Huang and others) about depleting aquifers in different parts of the world, we did not see a quantitative measure of groundwater overdraft in critical groundwater-using regions such as the Indo-Gangetic plain and northeast China. This information has to be calculated before truly comprehensive water balance for the future can be projected at a global scale. Attempts to do this using remote sensing by Richey and others are briefly reviewed later in this paper.

On the demand side is the slowing but ever-present growth in population. Mark W. Rosegrant's paper characterizes the complex relationship between agriculture, water, food, and population and diet using the comprehensive International Model for Policy Analysis for Agricultural Commodities and Trade (IMPACT) developed by the International Food Policy Research Institute (IFPRI). The results show an improving but not rosy future with reductions in the number of hungry world citizens and improvements in many diets. The extent to which current trends of income and meat consumption can be maintained is a pertinent question, as is the effect of biofuel production on food supplies. Rosegrant examines the effects of droughts and floods and the general linkage of water to economic growth using both the Impact modeling suite and results from a computable general equilibrium model. The results show a sharp increase in the price of cereals and potential decrease in the price of meat, with moderate increases in fruits, vegetables, and pulse crops. Using model projections out to 2050, the results show significant reductions in the world population at risk of hunger in Southeast Asia, South Asia and sub-Saharan Africa. The Middle East North and North Africa show small increases in the population at risk of hunger.

Rosegrant also surveys adaptation to increased water scarcity and new technology, plant breeding, farming systems, and institutional changes in water rights. The model shows there is still some potential for capital investment in irrigation water supplies. In particular, Central Africa has potential for 16 million additional hectares of large-scale irrigation and 50 million hectares for small-scale farms. These scenarios show a significant percentage change in cereal production and consumption and, consequently, a reduction in the risk of hunger. Like many of the speakers, Rosegrant projects a relatively slow growth in agricultural productivity and some progress in reduction of risk of hunger. Under a plausible scenario, the model shows a significant improvement in water and food security outcomes. However, Rosegrant notes that the model predictions fall short of the optimistic United Nations Sustainable Development Goals of eliminating hunger by 2030.

In contrast, Cassman's analysis of yield gaps in many major food crops and the potential to close these gaps through genetic improvements is more somber. He emphasizes the role of risk and decreasing returns on yield gaps in both developed and developing economies. He notes that growth in yield advances has been stable in recent years and finds no evidence that the exponential rate of gain in yields needed to close the production gap in many developing countries is forthcoming. the *Global Yield Gap and Water Productivity Atlas*, which includes both the mean crop yield and its coefficient of variation, show the distribution of crop yield gaps. Cassman also shows the effect of irrigation and rainfall on maize production in Nebraska and Iowa and draws parallels using the mean and coefficient of variation of maize yields in parts of Nebraska and rainfed maize-growing environments in sub-Saharan Africa. The effect of irrigation on simultaneously increasing mean yield and reducing the variation in yield is striking. Cassman proposes measures to evaluate the productivity of irrigation applied to maize in terms of water productivity measures. While he expects significant improvements in yields and productivity from innovations and agronomic and genetic practices, Cassman feels we have yet to use the true potential of big data on crop management, soils, and climates.

In his comments, Patrick Westhoff attributed much of the growth in grain demand to biofuel use and growth in per capita consumption in China. He argued that both of these trends will moderate. Rosegrant's paper presents a less optimistic view in a graph plotting per capita meat consumption against gross national income per capita. This is a reminder that food tastes as well as population numbers are shifting:

the trend of increased animal protein in the diet implies a strong upward shift in water demand despite a stable population.

II. Technical and Institutional Change

Technical change in irrigated agricultural production can be grouped into hydrologic technology changes, agronomic technology changes, and genetic technology changes. All three technologies can change the critical relationship between water use and agricultural production; however, the papers stress significant differences in how they influence fundamental water productivity between developed and developing countries. Hydrologic technology usually focuses on the field efficiency of irrigated production, defined as the ratio of applied water to the quantity of crop produced. Several speakers stressed that in developing countries, improvements in field efficiency often do not reduce net water use due to rational behavioral responses by farmers, who increase the area of irrigated production or shift crops to take advantage of the new efficiencies. This is an example of the Jevons paradox, which has changed the perception of the value of subsidizing field efficiency to induce water savings, a widely adopted water policy in developed and developing economies. In contrast, in her discussion of the paper by Scheierling and Treguer, Qiuqiong Huang stated that government-sponsored programs to improve field efficiency in China have been very effective in reducing net water use. She concluded that this is due to the small-scale and intensive nature of Chinese agriculture that prevents farmers from increasing water use in other crops or areas and undermining the gains in productivity from the improved field efficiency.

Cassman's paper emphasizes agronomic technology shortfalls expressed by the gap between potential yield and realized yield. He shows this yield gap is rarely less than 20 percent due to the increased risks and decreasing rates of return when farmers increase input use per acre much beyond this. One solution to this yield gap might be subsidized index insurance to shift some of the risk of closing the yield gap from farmers to national agencies. Another interesting finding is that much of the growth of yield realized in developed countries can be attributed to improved agronomic practices and mechanization rather than changes to the fundamental genetic stock.

The potential for substantial shifts in irrigated productivity due to genetic improvement was presented from two different perspectives. Cassman was not optimistic about the potential for genetically modified organisms (GMO) or clustered regularly interspaced short palindromic repeats (CRISPR) technologies based largely on data from developed countries' irrigation productivity. He was unable to find any dramatic gains in productivity resulting from these new approaches to plant breeding compared with advances due to new agronomic technology. In addition, many developing countries are reluctant to adopt GMO crops, as these crops may reduce their ability to export crops to some developed countries.

The paper's discussant, John Hamer, presented a contrasting view from the perspective of private industry. Hamer stated the current developments of both drought-resistant characteristics and significantly improved productivity from changes in genetic stock were proceeding rapidly and successfully. He cited examples where information from small start-up companies was leveraged by Monsanto and other companies. A critical factor for future crop adoption that came up in discussion was whether the new CRISPR gene technology will be characterized by the same stigma that currently impedes GMO technology. There was no consensus on this question.

Institutional changes to adapt to increased water scarcity also differ tremendously between developed and developing countries. In the context of developing countries, the conference papers on institutions focus almost exclusively on the optimal ways to implement water markets under different institutional circumstances. Mike Young's paper on the development of water markets in Australia presents a strong case for a wholesale modification of water property rights from the standard usufructuary water rights such as "prior appropriation" to those based on shares of the existing system. He stresses that there needs to be a clear demarcation between permanent rights as shares in a system and the annual allocations to those shares. His paper demonstrates dramatic changes in the net value of water in Australia over the last 10 years and emphasizes the importance of low transaction costs and a clear title to water. In addition, it is important to establish environmental water rights that can be traded on the same basis as other uses. In his comments on Young's paper, Nicholas Brozovic discussed the adoption of water markets in the United States and stressed the "path dependency" of institutional adoption. While he agreed with the principles that Young uses to define tradeable water rights, he was less sanguine about the difficulties of adopting a system similar to the Australians in the United States.

Despite these caveats, there is no question that the commoditization of both ground and surface water is a strong trend in many developed economies. Given the experience with other commodities, it seems that this trend toward pricing as an allocation mechanism for agricultural water and environmental uses will advance steadily and take the form of different institutional systems. Growing scarcity is driving the realization that despite significant environmental and social externalities associated with water use, water has all the fundamental characteristics of a commodity. The commodity properties are that it is highly substitutable across uses and locations, that a particular location of supply does not have unique characteristics despite the labels on bottled water, and that it can be stored without serious deterioration in quality.

One interesting exception to the market-based focus of the papers on water institutions in developed countries is the success of Natural Resource Districts (NRDs) mentioned by several conference participants. These districts have been established in Nebraska since 1972. There are 23 NRDs that control groundwater extraction by balancing artificial and natural recharge on a regional basis. The improved natural recharge of aquifers in Nebraska significantly helps the success of NRDs. Simple controls govern pumping within the districts, and most importantly, there is local control of pumping, monitoring, and enforcing simple control rules. Part of the success of Nebraska's NRDs may be that they are consistent with the principles of self-governing institutions proposed by Elinor Ostrom and discussed in the next section. Local control and enforcement is perhaps the most important principle of self-governance. Qiuqiong Huang's comments on Chinese irrigation institutions provided a counterpoint to the emphasis on markets in developed countries' economies. In China, the current emphasis is on subsidized technology in command-and-control systems for water allocation. Huang told us that water markets allocate groundwater in China, but there are mechanisms to restrict excessive pumping.

III. Some Omitted Topics in the Symposium

Despite the comprehensive topic coverage in the formal papers, I think that three topics important to understanding an agricultural water economy were underrepresented in the presented material. These topics are endogenous institutions, water quality degradation, and remote sensing methods for water and land use. A brief overview of these topics follows.

Endogenous local institutions

A significant omission from the discussion of institutions in conference papers is the work of Elinor Ostrom, the only person to receive the Nobel Prize in economics for work in resource economics. Ostrom's seminal work studied how small, self-governing, participatory institutional mechanisms arose from collective action in traditional societies. In particular, she focused on the management of common property resources which originated in the story of competitive water pumping from groundwater basins around Los Angeles area in the early 20th century and then was extended to analyze common property institutions in many other countries.

Ostrom developed eight principles for the collective choice management of resources under common property situations. She emphasized the need for consistency between appropriation and allocation rules, a point Mike Young makes in his paper on Australian water markets, and the benefits of locally based monitoring, measuring, and enforcement with graduated sanctions. Ostrom's work has made many contributions to both the design of optimal market mechanisms for water and, more importantly, the principles that will allow community-based management of common property resources. In developing countries, the clear and tradable property rights needed for water markets may be socially, physically, and economically impractical. By defining the community as the minimal management unit, the transaction costs of management can be greatly reduced. Rather than direct management of water allocations, the government can indirectly manage these water resources by providing information on village-level resource use and financial support for the village-level monitoring and enforcement of local rules. A potentially practical institution for water management in developing countries is one where control is decentralized to local units that may follow the process of community management based on Ostrom's principles. This combination of local control and centralized provision of information was raised by several speakers at the conference in the context of the system of Resource Management Districts in Nebraska. Resource Management Districts seem to have strong parallels with Ostrom's principles in that they rely on information on groundwater systems provided by state agencies but set and enforce their own management rules. Additional discussion of the implementation and principles behind Ostrom's work can be found in Cox and others.

Water quality for domestic consumption and agriculture

While the conference discussed managing water quantity extensively in a very wide range of aspects and levels of development, water *quality,* which is inextricably linked with water quantity use, was not discussed in any of the papers or questions from the audience. It may be no exaggeration to state that in several parts of the world, the degradation of groundwater quality by salinity, nitrate, and heavy metal accumulation is a greater threat to future use of that water resource than overdrafting. As we are often reminded, salinization has caused the collapse of many ancient traditional irrigation societies. Given the inevitability of saline concentration from the process of irrigation and evapotranspiration from external water supplies, agricultural irrigation systems cannot achieve a steady-state saline level without sources for external drainage and flushing of salts from the root zone. The need to flush excess salts from the root zone contradicts the fundamental nature of improving irrigation field efficiency. On the other hand, more efficient irrigation systems reduce the deep percolation and thus the transport salts into the online groundwater aquifer. For steady-state irrigation, one needs to strike the optimal balance between the minimal leaching fraction to maintain a salt-free root zone and that required for maximum efficient use of available water supplies.

Another source of degraded groundwater quality due to agricultural irrigation is excessive nitrate leaching. Given the high level of nitrate application in many irrigated crops, it is unusual for much more than 50 percent of the applied nitrates to be removed in the crop material, leaving the remaining nitrates to leach down through the root zone (although some of them are transferred to the air by volatilization).

The quantity of nitrates leaching into the groundwater is a function of the rate of nitrate applied to the crop and the time nitrate resides in the root zone, which is determined by the method of irrigation and the leaching fraction that results from it. More efficient irrigation methods, such as drip, reduce the nitrates leached into the groundwater, as they allow a greater residence time of the water and dissolved nitrates in the roots. Thus, a greater proportion of nitrates is taken up by the plant and removed as vegetative matter. The same relationship between application and water efficiency applies for the source of other groundwater contaminants, namely, heavy metals and pesticide residues.

While salinity is a major concern since it decreases crop yields, the level of nitrate pollution of groundwater has substantial public health costs, most particularly if young children are exposed to it through a supply of drinking water. Nitrate poisoning in young children is often known as blue baby syndrome. In many rural irrigated regions in both developed and developing countries, nitrate levels above safe drinking water levels persist. However, many rural water sources still have to rely on contaminated groundwater, which imposes costs and risks on a population sector that is least able to offset these risks with other sources of water or move to other locations. Clearly, nitrate and pesticide contamination leaching into groundwater is a major problem in many irrigated areas.

Emerging information systems for improved water management

Many of the water management institutions discussed and criticized in the conference papers are forced to manage using proxy variables due to the cost and difficulty of precisely measuring water use on a scale suited to management. This is one area in which substantial and recent breakthroughs due to better information technology systems may have a real chance of changing the precision with which water can be managed while simultaneously reducing transaction costs. Two different systems using remote sensing promise to measure surface water evapotranspiration and changes in groundwater volume with greater precision than currently available. The first system is the Metric (Sebal) method, which uses an energy balance measure from the Landsat satellites and climate data from local ground-based sources to calculate evapotranspiration (ET) for each 40 x 40 meter pixel every one to two weeks depending on cloud cover and satellite passes. The second system uses data from NASA's Gravity Recovery and Climate Experiment (GRACE) systems to estimate changes in groundwater stocks over large, basinwide geographic areas.

The Metric ET method has been extensively tested over the past 15 years and found under many conditions to have a high level of accuracy compared with standard field lysimeter-based ET measures. (Allen and others). In Idaho, where most of the pioneering work on this method has been done, Metric is accepted as reliable information on which to base the settlement of water rights in the Idaho courts. This ability to accurately measure net water use on a field, farm, or basin scale enables users and managers to calculate the net withdrawals from groundwater as long as surface water supplies are relatively accurately measured. In addition, using the Metric system to estimate water use shows considerable savings in transaction cost over conventional methods. A comparison in Idaho shows that conventional metering costs $119 per well per year, while comparable estimates using Metric cost $32 per field per year. When Metric is more widely used, additional economies of scale should be achievable. Estimations using Metric are now being used for water management in several other western states.

Groundwater stocks can also be measured by remote sensing. Richey and others use the GRACE satellite system to measure changes in groundwater stocks on a global basis. Currently, the GRACE system is normally aggregated at a scale that precludes its use for individual basin management but presents an invaluable method of assessing changes in groundwater stocks on a consistent and accurate basis worldwide. Richey and others measure groundwater stress in 37 of the world's major basins. They use a general measure of renewable groundwater stress (RGS), which, similar to Scheierling and Treguer's paper, is defined as the ratio of use to estimates of availability. Richey and others use the trend in subsurface storage anomalies over the study period to quantify the change in groundwater by accounting for withdrawals, capture, and changes due to natural factors such as drought. Their results show that eight aquifers are overstressed based on RGS_{GRACE}, and 13 of the study aquifers are variably stressed based on RGS_{GRACE}. Seven of these systems are in the low stress category including the Ganges, where there is a high rate of mean annual recharge. Thirteen aquifers are characterized as unstressed: these are mainly located in remote forested areas and rainfed regions with an absence of irrigated agriculture.

Famiglietti and others apply GRACE measurements to depletions to aquifers in California's Central Valley over a 78 month period. Their results show a greater rate of groundwater depletion (which may well be unsustainable) than other methods, with potentially dire consequences for economic and food security.

IV. Summary

The conference presented a series of provocative and challenging papers that ran the gamut of interactions between water and agriculture in developing and developed economies. The key consensus throughout the conference was the increasing scarcity of water due to both supply reductions (due to climate change and overdrafted aquifers) and a strong increase in demand (due to increasing populations and shifts in diet). While there is not clear agreement among the speakers, there was a consensus that continuous advances in both institutional and technological responses to increased water scarcity would be forthcoming in developed and developing agricultural economies. In developed countries, irrigated agriculture will continue to increase productivity. At the same time, developed countries will respond to ever-increasing environmental requirements by adopting more of a market orientation toward water allocation to redistribute scarce water resources over time, location, and economic sectors.

Developing countries face a more challenging situation due to the twin problems of a growing population and shifts in diet toward greater meat consumption. In addition, developing countries probably face similar constraints on future groundwater extraction due to the current level of unsustainable overdrafting. Some speakers noted that institutional change toward a market orientation may not work as well in developing countries due to problems of property rights, transaction costs, tradition, and enforcement. However, several speakers show that there is significant potential to improve irrigated agricultural production in developing countries.

Finally, I apologize to those speakers whose views I may have misrepresented and to those whose prescient insights I may have overlooked. Any omissions are entirely my fault, with my only excuse being the pace and intensity with which this successful conference evolved.

Endnote

[1]Basins that are currently severely overdrafted are in the Middle East, the Indo-Gangetic plain, the Ogalalla foundation under the U.S. High Plains, California's Central Valley, and parts of northeast China.

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Economic Review

Special Issue, 2016

The *Economic Review* (ISSN0161-2387) is published quarterly by the Federal Reserve Bank of Kansas City, 1 Memorial Drive, Kansas City, Missouri 64198-0001. Subscriptions and additional copies are available without charge. Send requests to the Public Affairs Department, Federal Reserve Bank of Kansas City, 1 Memorial Drive, Kansas City, Missouri 64198-0001. Periodical postage paid at Kansas City, Missouri.
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Special Issue 2016