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 determined by water supply 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.

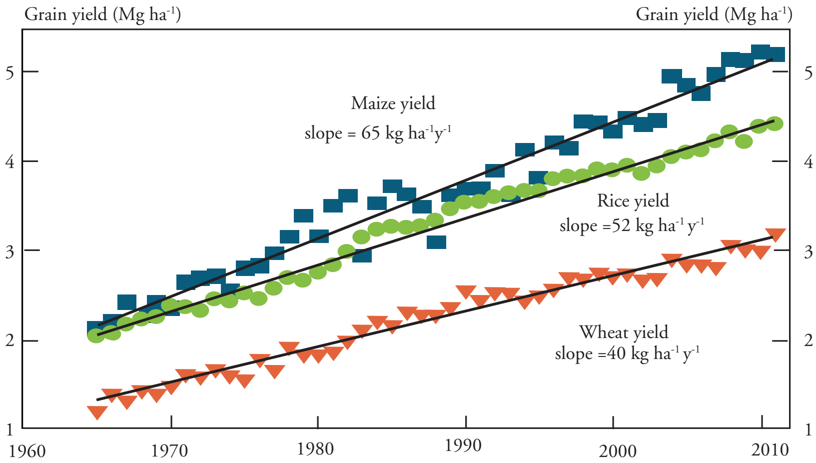
Hence the grand challenge is achieving a 50–100 percent yield increase on the existing area of cropland while also making substantial improvements in the efficiency with which inputs are used—a process called ecological intensification (Cassman). The remainder of this paper evaluates several key components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

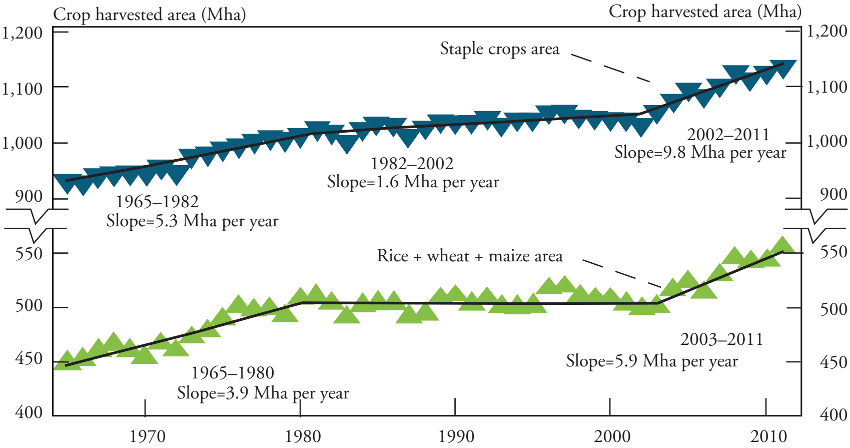
However, aggregate global rates of yield growth for major food crops have followed a decidedly linear path for the past 60 years: relative rates of gain (the ratio of the linear rate of increase to the yield in a given year) fell from 2.5 to 3.0 percent in 1965 to 1.2 to 1.3 percent in 2011 (Chart 1). 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.

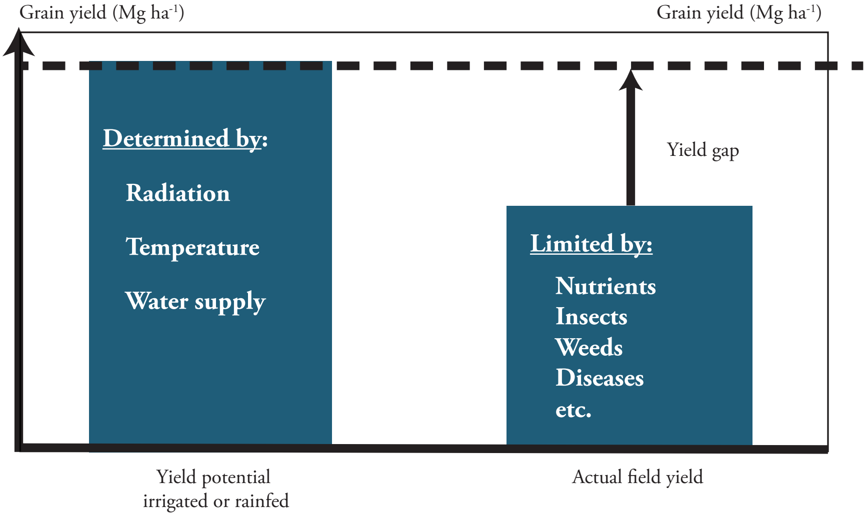
Another reason for yield stagnation is that average farm yields have approached the biophysical yield ceiling determined by climate and rainfall—factors not modified by management. For irrigated crops with adequate water to avoid deficits, the biophysical yield ceiling is called yield potential (Yp) 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



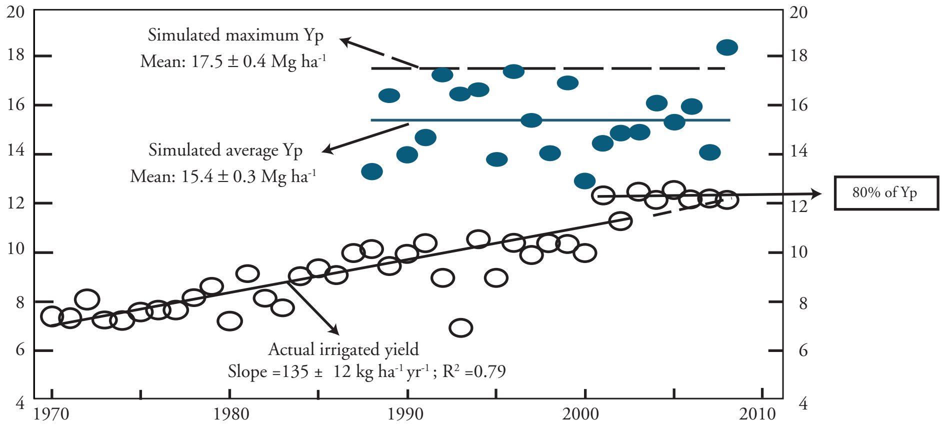
in some cases, though high seed costs and a greater risk of lodging and disease in dense plant stands give diminishing returns.

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.

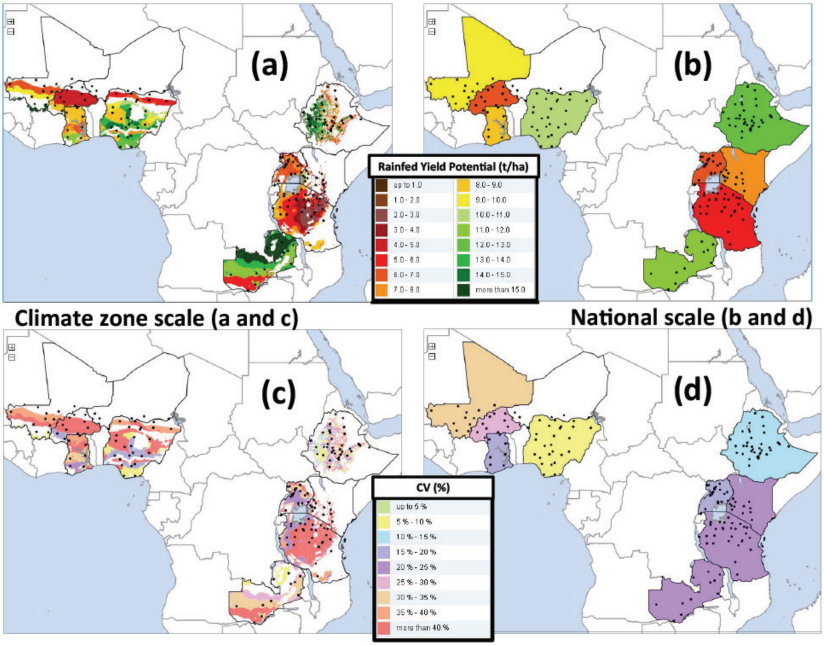
IV. Estimating Food Production Capacity at Local to Global Scales

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*



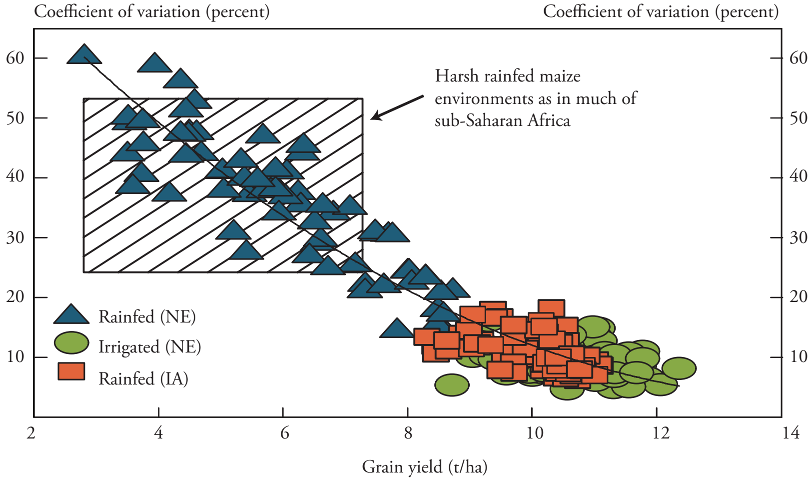
Note: Screenshots A and B show rainfed maize yield potential. Screenshots C and D show the coefficient of variation due to yearly variation in weather shown as a percentage of yield potential. Data are mapped at two spatial scales: climate zones (A and C) and country (B and D). The data are also available 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.

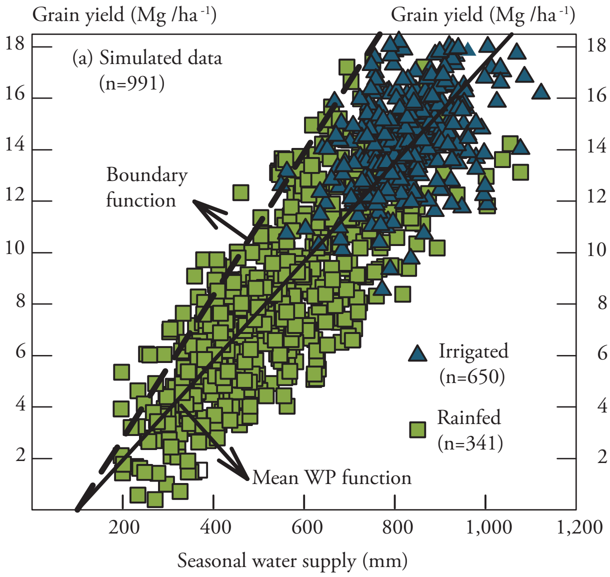
In general, however, irrigation is relatively inefficient worldwide because both water and energy were inexpensive during the 1950–90 period when most large-scale irrigation systems were designed and developed. Typical irrigation systems installed during that period relied on surface irrigation, which 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

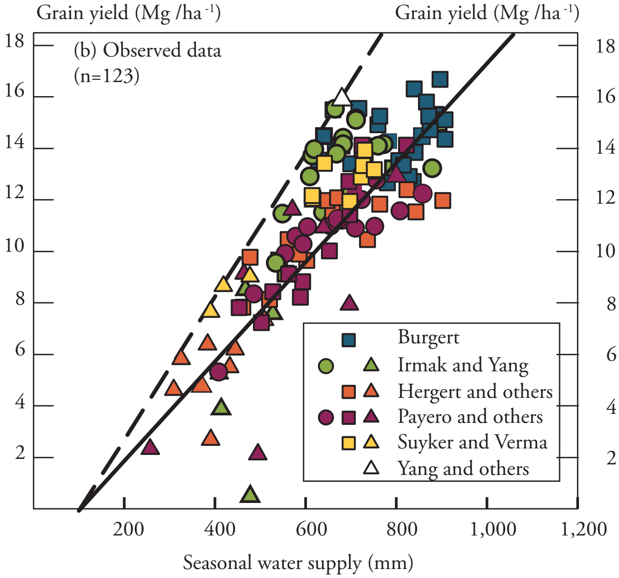
Chart 5

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.

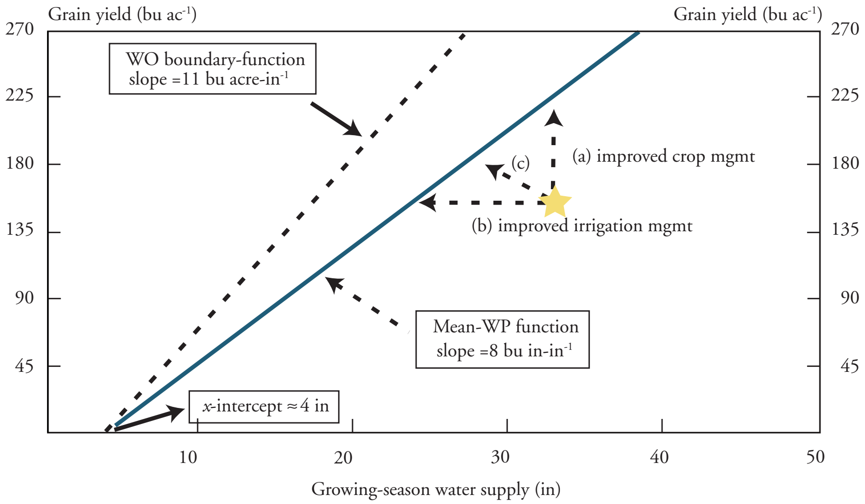
The most appropriate WP benchmark for a population of farmers is the mean WP function line as shown in Panel A of Chart 5 for two reasons. First, this function accounts for expected variation in weather. Second, it has been rigorously validated across a wide range of environments in carefully managed 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



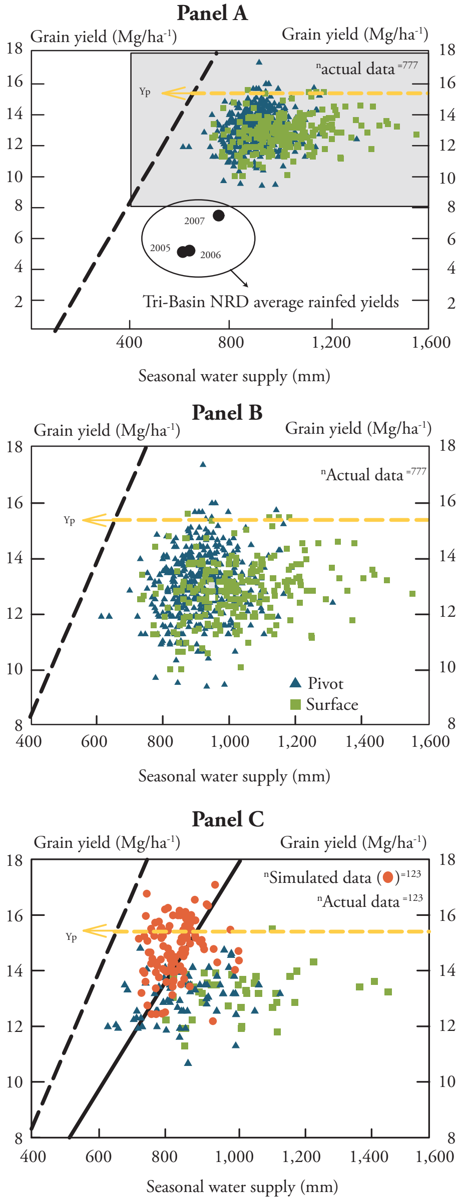
Notes: Chart shows performance of an individual farmer's field (★) relative to WP benchmark functions and options for increasing WP by better management to give higher yields with the same total water supply through improved agronomic practices (arrow a, including choice of cultivar, sowing date, stand 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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