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Long-Term Trajectories: Crop Yields, farm land, and irrigated agriculture

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The primary thesis of this paper is that the specter of global food insecurity, in terms of capacity to meet food demand, will not be limited by water per se or even climate change, but rather by inadequate and misdirected investments in research and development to support the required increases in crop yields. A secondary theme is that the magnitude of this food security challenge is further augmented by the need to concomitantly: (i) accelerate rate of gain in crop yields well above historical rates of the past 50 years during the so-called green revolution, and (ii) substantially reduce negative environmental impacts from modern, science-based, high-yield agriculture. While these themes may at first seem pessimistic, they also point the way towards solutions that lead to sustainable food and environmental security. To identify the most promising solutions requires robust assessment of crop yield trajectories, food production capacity at local to global scales, the role of irrigated agriculture, and water use efficiency.

Magnitude of the challenge

Much has been written about food demand projections in coming decades with increases of 50 to 100%% required by 2050 for major food crops (e.g. Bruinsma 2012; Tilman et al, 2011). The preferred scenario to meet this demand is to do so with minimal conversion of natural ecosystems to farm land, which avoids both loss of natural habitat for wildlife and biodiversity and large quantities of greenhouse gas emissions associated with land clearing (Royal Soc. London, 2009; Burney et al., 2010; Vermuelen et al., 2012). While efforts to reduce food waste and meat consumption can contribute modestly to decreased 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 policy makers responsible for food security is to ensure that 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 the existing farm land area, however, does not mean zero conversion of non-agricultural land to crop production due to urban sprawl. Seto et al. (2012) project global urban expansion of 130 million hectares by 2030. Because most cities are located in areas surrounded by farm land, meeting food demand in 2050 on the current 1.5 billion hectares base area means converting upwards of 100 million hectares of non-agricultural land to crop production.

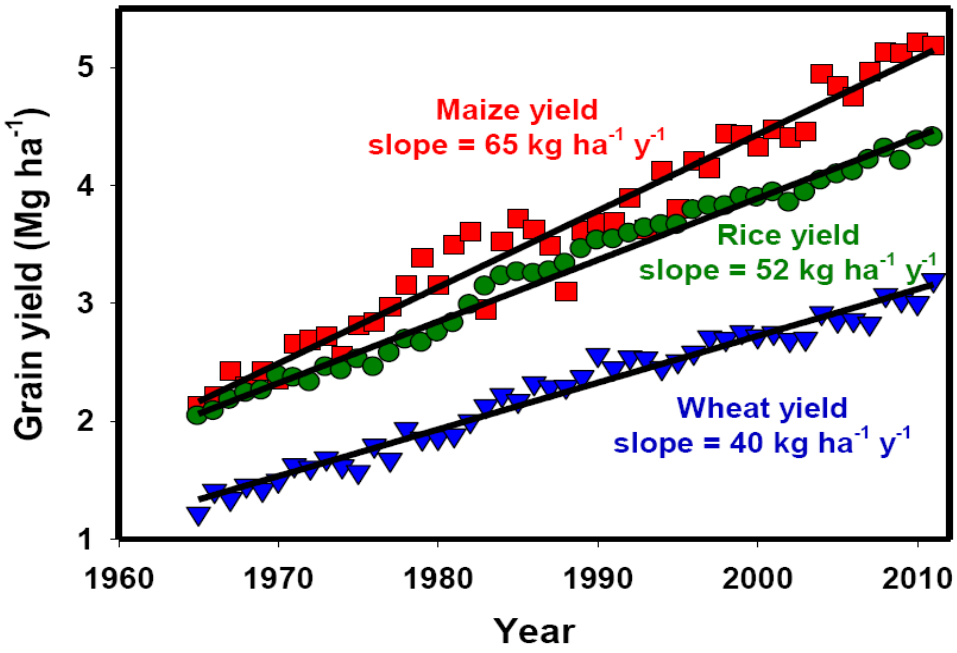
In addition to producing sufficient quantities of food to meet demand, production systems must also greatly reduce current negative impacts on environmental quality and human health (e.g. Horrigan et al., 2002) and alleviate pressure on use of natural resources (Green et al., 2005; Scanlon et al., 2007; Lawrence et al., 2013;). 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 and raising input use efficiencies can reduce negative environmental impacts if such reductions can be achieved while also supporting continued growth in yields.

Hence the grand challenge is to achieve a 50-100% yield increase on the existing area of crop land while also making substantial improvements in the efficiency with which inputs are used—a process called ecological intensification (Cassman, 1999). The remainder of this paper will evaluate a number of key components embodied in this challenge.

Are current yield growth rates fast enough?

To achieve a 50 to 100% increase in cereal yields by 2050 requires 1.2 to 2.0% annual exponential yield growth rates. In contrast, aggregate global rates of yield growth for major food crops have followed a decidedly linear path for the past 60 years, and thus relative rates of gain (ratio of linear rate of increase to the yield in a given year) have fallen from 2.5 to 3.0% in 1965 to 1.2 to 1.3% in 2011 (**Figure 1**). If current linear trajectories are maintained, relative rates of gain will fall below 1.2% by 2020 for all three cereal crops, which means current rates of increase are much slower than required to meet projected demand by 2050 on existing crop area. Instead, rates of gain must accelerate well above trajectories of the past 50 years if food demand can be met without massive expansion of global crop area.

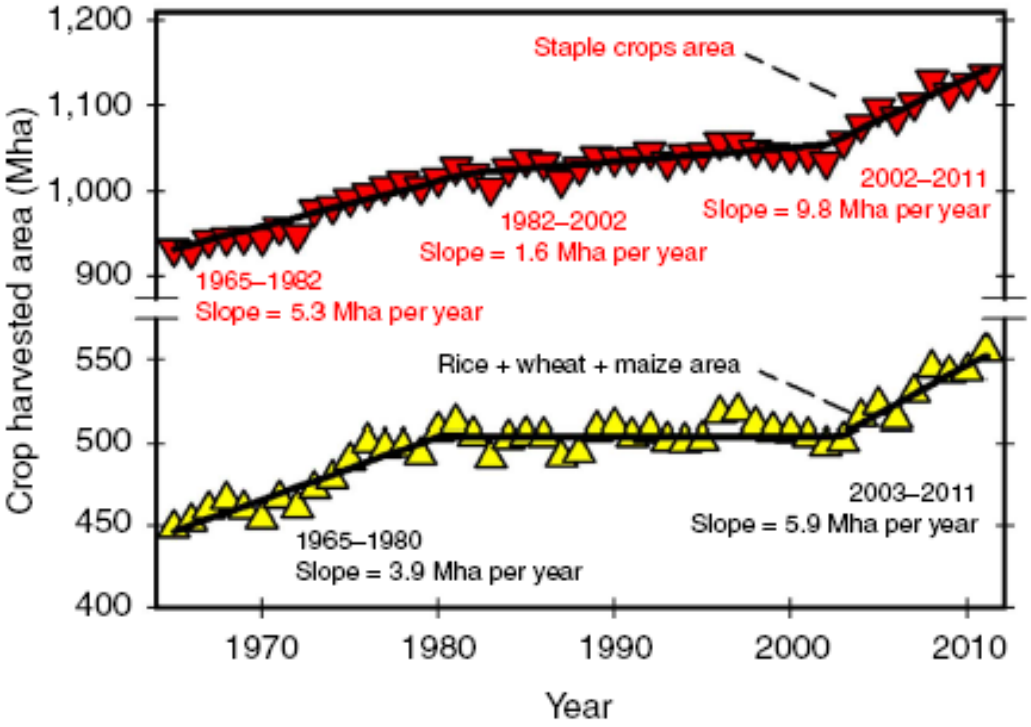
Figure 1. Global yield trends in of the major cereal crops. Data from FAOSTAT, http://faostat.fao.org/site/339/default.aspx.



Evaluation of aggregate global yield trends mask important differences among countries. Using a robust spline regression approach, Grassini et al (2013) recently documented that yields of major cereals have stagnated or declined significantly in countries that account for 31% of total production. Stagnant yields are evident for rice in China, Korea, and California, and wheat in most of western and northern Europe and India. At issue is the cause of this stagnation and whether yield trends in other major crop producing countries will follow suit.

Because yield growth is not keeping pace with food demand, there is increasing pressure to expand crop production area. In fact, harvested crop area has been increasing at an annual rate of 10 Mha since 2002 (**Figure 2**), which is faster than at any time in human history. About 60% of this increase is due to increased production area of the major cereal crops: maize, rice, and wheat. When soybean, oil palm and sugarcane are also considered (data not shown), these six crops account for about 85% of the total increase. Unless rate of growth in crop yields accelerates well above historical trajectories shown in Figure 1, large-scale conversion of land to crop production will likely continue.

Figure 2. Trends in global harvested area from 1965 to 2011 for all staple food crops and for the three major cereals: maize, rice, and wheat. From: Grassini et al., 2013.



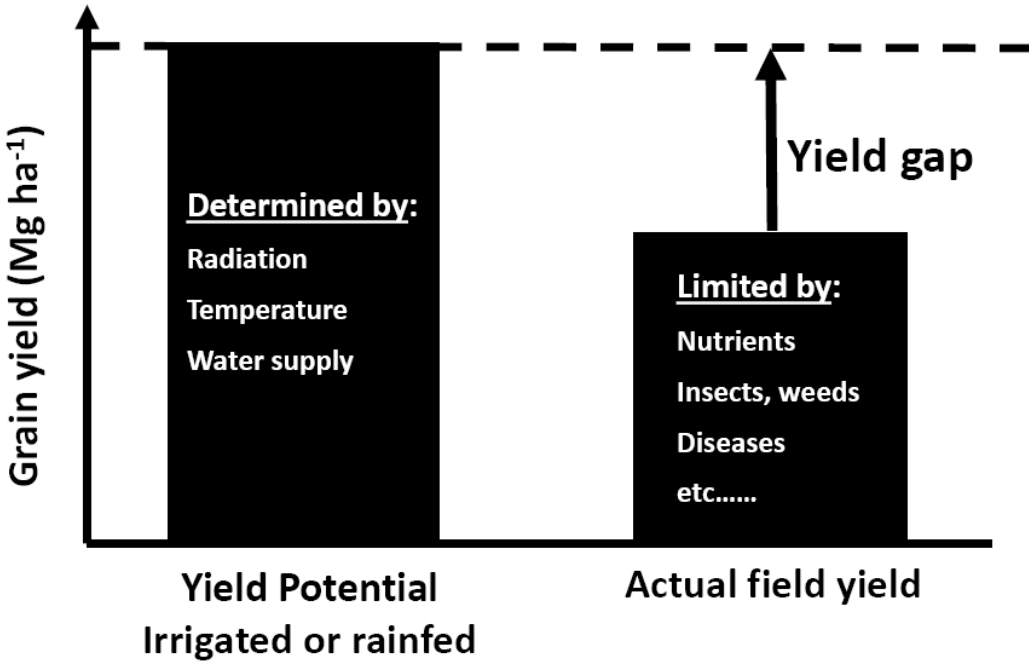
Biophysical yield limits and farm yield trajectories

Stagnating yields, or even yield decreases, can result from a number of factors such as 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 poor agricultural policies or economic turmoil that restrict affordability or access to production inputs or which decrease prices farmers can expect for their crops. Strict regulation of input use, such as N fertilizer or transgenic crops (also called "genetically modified crops", or GMOs) could also reduce the rate of yield gain.[1] Climate change and associated temperature increase may negatively affect yields although to date, a clear signal of negative impact is muted because the magnitude of temperature rise is not large and farmers can adjust management practices to both attenuate negative effects and take advantage of opportunities presented by warmer temperatures. Examples of opportunistic farming with warmer temperatures include earlier planting with longer-maturing cultivars and two crops per year where only one was planted previously.

Another reason for yield stagnation is because average farm yields approach 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 length of growing season, and the amount of solar radiation during the growing season. For 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 as shown in **Figure 3**.

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

Figure 3. Yield potential and yield gaps and determinants of each.



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. 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 (Richards and Hall, 2013). As result, Yp and Yw of maize and rice have remained little changed over the past 50 years (Duvick and Cassman, 1999; Peng et al., 1999) while there has been modest improvement in the genetic yield ceiling of wheat (Cassman, 1999).[2]

At the field level, farmers can 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 there are risks associated with a longer growth period from greater chance of damaging weather events (e.g. 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 in some cases although high seed costs and greater risk of lodging and disease in dense plant stands give diminishing returns to this tactic.

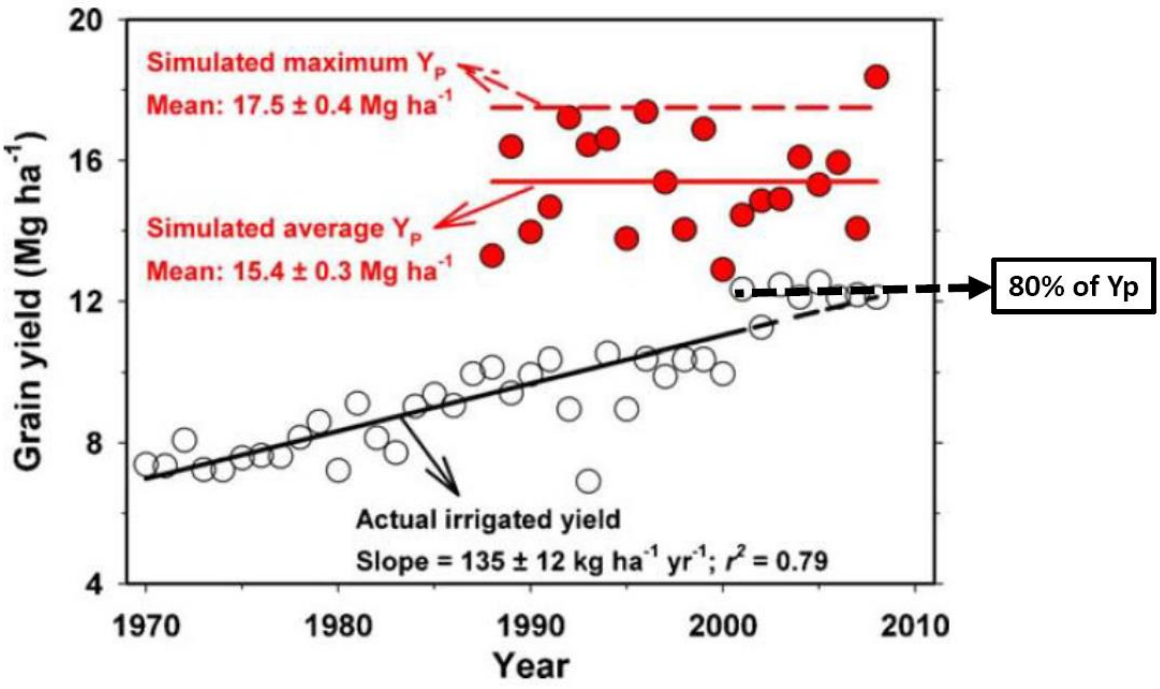
Indeed, farmers do not strive to achieve maximum yields and instead try to maximize profit. Maximum profit is obtained at a yield level below Yp or Yw because there are diminishing returns to increased use of inputs such as fertilizer, water, seed, labor, and pest control measures as yields rise towards the yield ceiling. Hence average yields begin to plateau for a population of farmers when their average yield reaches 75 to 90% of the Yp or Yw yield ceiling (Cassman, 1999; Cassman et al., 2003). The relative

[2] Other authors suggest that 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 use of different assessment methods with greater reliance on trends from historical varietal yield trials and contest-winning yields (e.g. Fischer et al., 2014).

yield at which stagnation occurs reflects the risks associated with obtaining a return on investment from use of additional inputs and the price ratio of inputs versus grain (Lobell et al., 2008).

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 found yield stagnation occurred at 82% of Yp, whereas stagnation of wheat yield in Germany occurred at 80% of Yw (Van Wart et al., 2013). For irrigated maize in central Nebraska, stagnation is beginning to appear at 80% of Yp (**Figure 4**, from Grassini et al, 2011a). In that study, a Yp of 15.4 Mg/ha (equivalent to 15.4 metric tonnes per hectare, or about 250 bu/ac) is 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% to 17.4 Mg/ha. But there is little barrier to adoption of these options, which means that NE 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 et al., 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 per se.

Figure 4. 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 red circles and red line), and (2) optimal management to maximize yields as discussed in the text. Suggested yield stagnation since 2001 occurs at a yield that is 80% of yield potential with current management.



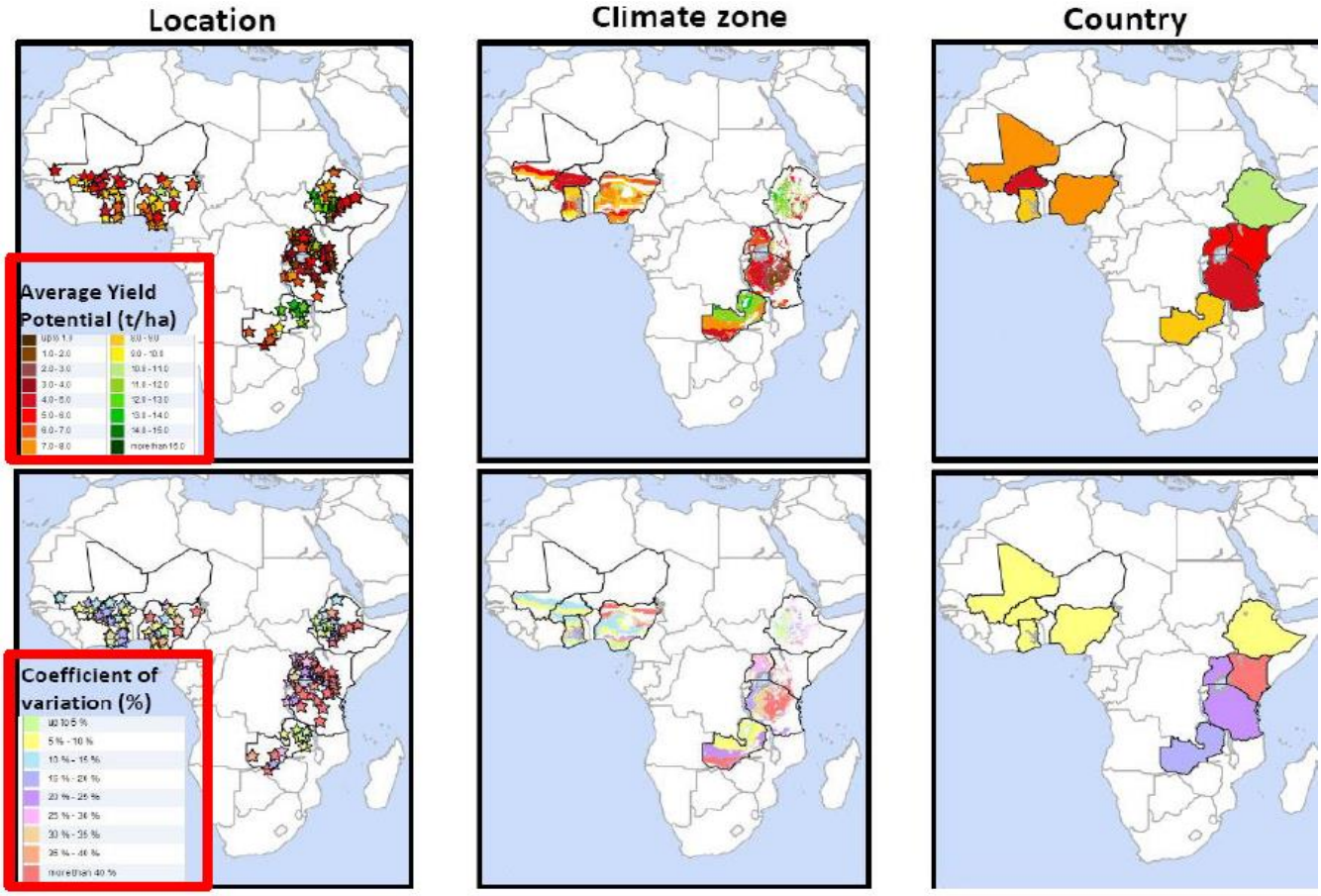
Estimating food production capacity at local to global scales

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 farm land. To this end, the Global Yield Gap Atlas (www.yieldgap.org) has completed detailed yield gap

assessments of major crops in 22 countries. 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 (e.g. Licker et al., 2010; Mueller et al., 2010), the Global Yield Gap Atlas relies on local primary data to the extent possible coupled and a robust “bottom-up” scaling technique that provides yield gap estimates at local to global levels (Grassini et al, 2015; van Bussel et al., 2015). 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 (**Figure 5).** 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, estimating Yg for a given country provides information about capacity to meet future national food demand from existing farm land assuming farmers can achieve an attainable yield that is 80% of 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 farm land and make plans about how best to ensure adequate, reliable, and affordable supplies. Options include expanding production area, imports, or both. The issue of reliability of supply becomes especially important for low-income, food deficit countries as seen during the global 2008 food crisis. Estimates of yield stability (i.e. coefficient of variation, Figure 5) provides a quantitative estimate of supply reliability from national or regional production.

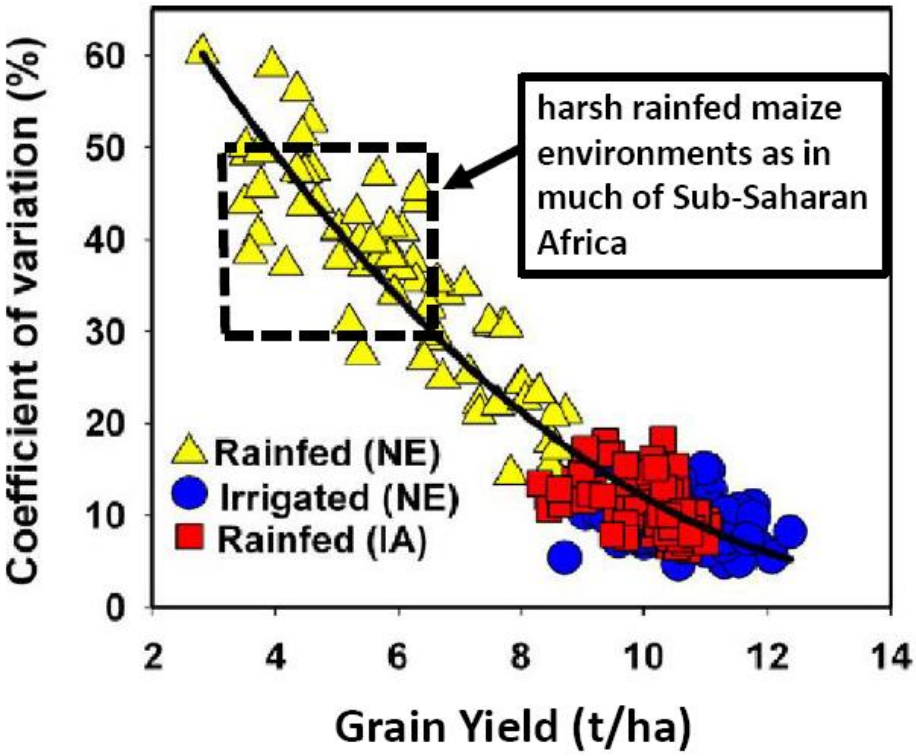
Figure 5. Screen shots from the Global Yield Gap Atlas (www.yieldgap.org) showing rainfed maize yield potential and coefficient of variation due to yearly variation in weather. Data are mapped at spatial scales from a specific weather station location, and aggregated upscaled to climate zone and country.



For example, in some cases a country, or a region like West Africa, may have sufficient production capacity to meet projected demand on existing rainfed farm land but stability of that supply is unreliable due to highly variable rainfall. Indeed, most of Sub-Saharan Africa (SSA) relies heavily on rainfed crop production because only 4% of current crop area is irrigated. And despite relatively high annual rainfall in much of SSA cereal areas, Yg analyses from the Atlas identifies yield stability as a major problem: The coefficient of variation in Yw in cereal yields is similar to that in the westernmost U.S. Corn Belt where temporal yield variability is also high (**Figure 6**). Low stability in SSA cereal yields despite generous rainfall amounts reflects warmer temperatures and greater transpiration demand than in the US Corn Belt. Expansion of irrigated area would be an option to help stabilize national and regional production if sustainable water resources are available to support it. One recent report suggests that food security in SSA depends on expansion of irrigated area (Cassman and Grassini, 2013). Moreover, hydrological evaluations indicate adequate ground and surface water resources to support substantial expansion in irrigated area in some regions of SSA (e.g. MacDonald et al. 2012).

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 options for leveraging that capacity through investments in infrastructure and education to

Figure 6. Relationship between yield stability (quantified by the coefficient of variation) and average grain yield (2001-2010) from maize-producing counties in Iowa (IA) and Nebraska (NE). 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. Analysis from the Global Yield Gap Atlas (www.yieldgap.org) documents that most of rainfed maize production in West and East Sub-Saharan Africa have average yields and yield stability within the dashed box.



support it and to remain competitive in global markets. Argentina is a good example of a country with substantial capacity for increased crop production on existing rainfed farm land based on the recent yield gap analysis of Merlosa et al. (2015). Their analysis found current farm yields to be 59 to 68% of Yw Table 1). By raising average yields to 80% of Yw, Argentine farmers could produce an additional 7.4, 5.2, and 9.2 Mt of soybean, wheat, and maize on existing crop area, which represent 9%, 4%, and 9% of current global exports of these commodities.

Table 1. Current rainfed yields, yield potential, yield gaps, and national production capacity at 80% of rainfed yield potential in Argentina (Modified from Merlosa et al., 2015)

Crop	Current yield	Yield Potential	Yield gap	Current yield as % of yield potential	Crop area	National production capacity
	---------- t ha^{-1} ----------			%	Mha	Mt
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

Irrigated agriculture and food security

On a global scale, irrigated agriculture supplies about 40% of our human food supply on less than 20% of the farm land (FAO, 2008). In addition to the quantity of food produced, irrigated agriculture provides the "ballast" to local, regional, and global food supply in several ways. First, it is much higher yielding than rainfed crop production, especially in semi-arid and sub-humid climates. For example, in central and western Nebraska where both irrigated and rainfed maize are produced, irrigated maize yields currently average about 12 t/ha, which is nearly double the yields from rainfed maize. Second, yield stability is substantially greater in irrigated systems. In Nebraska, the coefficient of variation for rainfed maize in central and western Nebraska ranges from 30-60%, which is 4 to 8 times greater than for irrigated maize in the same region (**Figure 6**). 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.

Is irrigated agriculture sustainable?

High yields from irrigated crop production reduces pressure for an expansion in crop area. None-the-less, the fact that irrigated agriculture appropriates such a large portion of global fresh water withdrawals provides justification for a popular narrative that irrigated agriculture is not sustainable. But food prices would rise dramatically if irrigated agriculture was greatly scaled back, and meeting projected food demand without irrigated agriculture is simply not a feasible proposition. Hence the long-term viability

of irrigated agriculture and its future contribution to food security distills into two questions: (1) whether it is possible to maintain current area of irrigated production area while also accommodating other demands on surface water supplies and maintaining aquifers without over-drafting? and, (2) how much can increased water use efficiency contribute to expanding irrigated production area without an increase, or perhaps even a decrease, in 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 over-appropriated by a large margin (e.g. Wada et al., 2010; Hoekstra et al., 2012). Coupled with concerns about water scarcity and negative environmental impacts of reduced stream and river flow from water diversion for irrigation (e.g. Scanlon et al., 2007; Pfister et al., 2011; Rosegrant et al., 2013), a significant increase in irrigated area is unlikely. Instead, reduction in irrigated area in some regions where over-drafting and competition with non-agricultural uses are prominent may be offset by expansion in other regions. As previously mentioned, there is substantial potential for increased irrigated area in SSA as previously mentioned. Recent experience of irrigated agriculture in California, Nebraska, and Texas provide important insights into future global trends.

California's Central Valley is an example of a region where there is intense competition for water between agriculture and other sectors and total irrigated area has been in decline (Table 2). Aquifers are over-drafted (Scanlon et al., 2012), and environmental regulations and extended drought have reduced water supplies for irrigation. In 2015, the fourth consecutive year of severe drought, about 7% 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 highest value crops, invested in new wells and technologies to increase irrigation efficiency. The result was a relatively small impact on yields and a decrease in total crop value of less than 3% (Howitt et al., 2015). With normal rainfall in 2016, most major reservoirs in California have sufficient storage to meet normal irrigation water commitments although it will take many more years of above-average rainfall to replenish aquifers that have been heavily overdrawn.

In contrast to California, irrigated area in Nebraska continues to increase (Table 2), and Nebraska now has more irrigated crop area than any other state. This increase has occurred without over-drafting the northern High Plains Aquifer that sits under much of Nebraska (Scanlon et al., 2012), and this aquifer is the primary source of irrigation water supply. Proactive policies and a robust regulatory framework, as applied by the state's Natural Resource Districts (NRDs, https://www.nrdnet.org/), 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 both surface and groundwater and both federal and state laws governing water quality (Bleed and Hoffman, 2015). When aquifer levels fall below predetermined threshold levels, NRDs have 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, and water use in those few areas remain under tight regulation until water resources are in compliance. In contrast, water level in the southern High Plains Aquifer under Texas has seen substantial decline (Scanlon et al., 2012), and irrigated area in that state has decreased by 22% 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 over-appropriation.

Table 2. Changes in irrigated crop area from 1997 to 2012 in three states. Source: https://www.agcensus.usda.gov/Publications/2012/Online_Resources/Farm_and_Ranch_Irrigation_Survey/

State	Irrigated crop area ----------Million hectares----------	
	1997	2012
California	3.60	3.18
Nebraska	2.84	3.36
Texas	2.33	1.82

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 that water resources are not over-appropriated. Assuming effective regulations are in place, improving the efficiency with which irrigation water is converted to economic yield provides a powerful tool to maximize productivity of a limited water supply.

In general, however, irrigation efficiencies worldwide are relatively poor because both water and energy were inexpensive during the 1950-1990 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 species, water productivity (WP) represents a useful metric for evaluating water use efficiency of both irrigated and rainfed crop production and is calculated as the ratio of economic yield to total water supply. Total water supply includes: (i) stored soil moisture at sowing of annual crops or at beginning of the growing season in perennial crops, (ii) rainfall during the crop growth period, and (iii) 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 rainfall in irrigated production, and temperature, solar radiation, and rainfall in rainfed production (**Figure 7a, for maize**). Whereas the WP *frontier boundary* represents 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 variation in weather (Grassini et al., 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 35C (95F) in the critical 3-day pollination period, grain number will be reduced, which results in below-average yields although season-long water requirements may be average or above-average, thus resulting in a WP value below the *mean WP function* line. Likewise, a year with cool temperatures and bright sunny days during grainfilling results in 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 ear formation and early seed differentiation, pollination, and grainfilling.

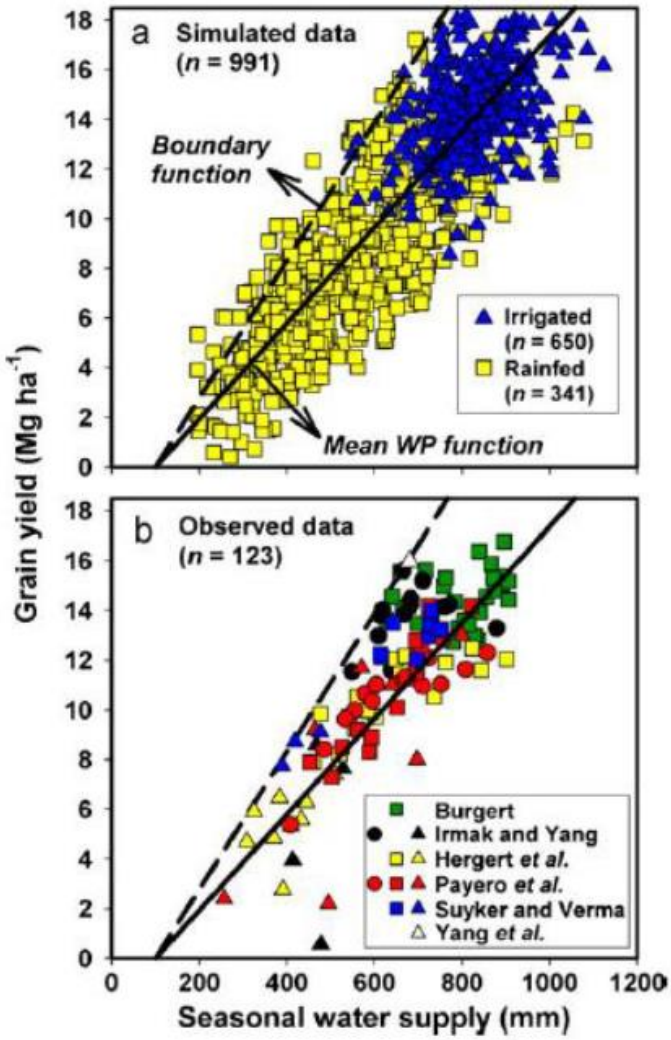


Figure 7. Relationship between:

(a) 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 et al. (2009b) as simulated over a 20-year period at 18 sites across the US Corn Belt. Dashed and solid lines are the boundary- and mean water productivity (WP) functions, respectively (slopes = 27.7±1.8 and 19.3±0.4 kg ha−1 mm−1, respectively; x-intercept = 100 mm).

(b) (b) Actual grain yield and water supply data from field studies in the Western U.S. Corn Belt managed to produce yields without limitation from nutrients or pests under rainfed (Δ), irrigated-sprinkler or pivot (□) or subsurface drip irrigation (o).

From: Grassini et al., 2011b.

The most appropriate WP benchmark for a population of farmers is the *mean water productivity function* line as shown in Figure 7a 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 (**Figure 7b**).

The WP framework can be used to evaluate the WP of an individual field (**Figure 8**) or for 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 by achieving higher water use efficiency, for example via modifications that improve irrigation timing, amount, and application method (e.g. pivot versus surface irrigation). In most cases the most cost-effective option for obtaining higher WP involves use of both improved 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 nearby several nearby weather stations for each field (Grassini et al., 2011a,b).

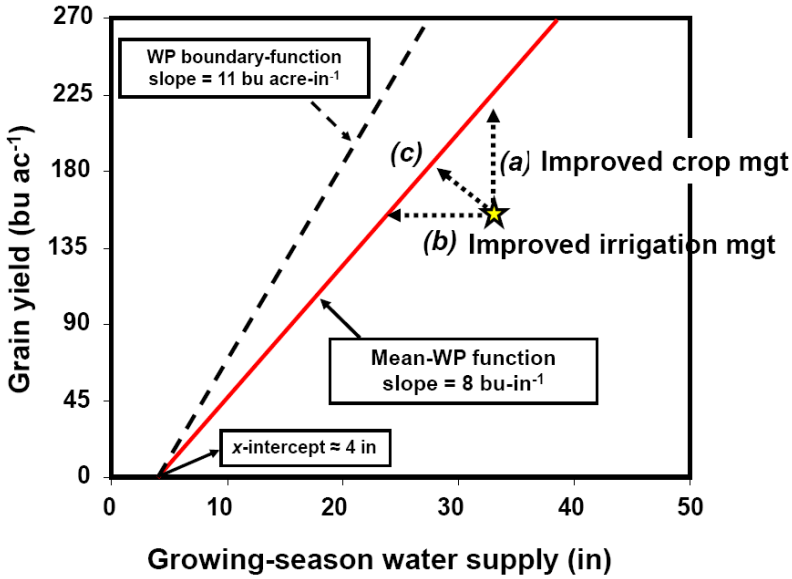


Figure 8. Performance of an individual farmer's field (☆) relative to water productivity (WP) benchmark functions, and options for increasing WP by better management to give higher yields with the same total water supply through improved agronomic practices (*arrow a*, including choice of cultivar, sowing 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 Figure 7, converted to English units for yield (bu/ac) and water (depth in inches).

Evaluation of farmer-reported data on maize yields and irrigation water application to over a 3-year period in the Tri-Basin Natural Resource District in central Nebraska provides an example of WP performance for a population of farmers in a watershed (**Figure 9**). In that NRD farmers are required to install a high quality flow meter on all irrigation wells and 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 (Grassini et al., 2011a), results documented a number of options to increase WP. The most promising included 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, adoption of all identified options by all farmers in the NRD would reduce NRD irrigation water requirements by 33% without a significant reduction in yield (Grassini et al., 2011b).

It is noteworthy that use of farmer-reported data over several years that 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 resulting high degree of confidence in identified options that give higher WP and the associated water savings. For example, while equivalent yields were obtained from fields with surface or pivot irrigation, applied irrigation was 41% less in pivot-irrigated fields (Figure 9b). Fields under conservation tillage received 64 mm (2.5 inches) less irrigation water than those conventionally tilled. The reason for such large water savings with conservation tillage is because crop residues left on the soil surface reduces evaporation and holds winter snowfall in place, rather than blowing off into snow drifts along field borders and roads, which results in a much larger amount of 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 because maize has a larger irrigation water requirement. Finally, use of crop simulation to estimate Yp based on actual crop management for sowing date, hybrid maturity, and plant population showed that a majority of farmers applied more water than needed to reach the biophysical yield ceiling although about 25% of farmers achieved high WP and were within 10% of the *mean water productivity function* line (Figure 9a).

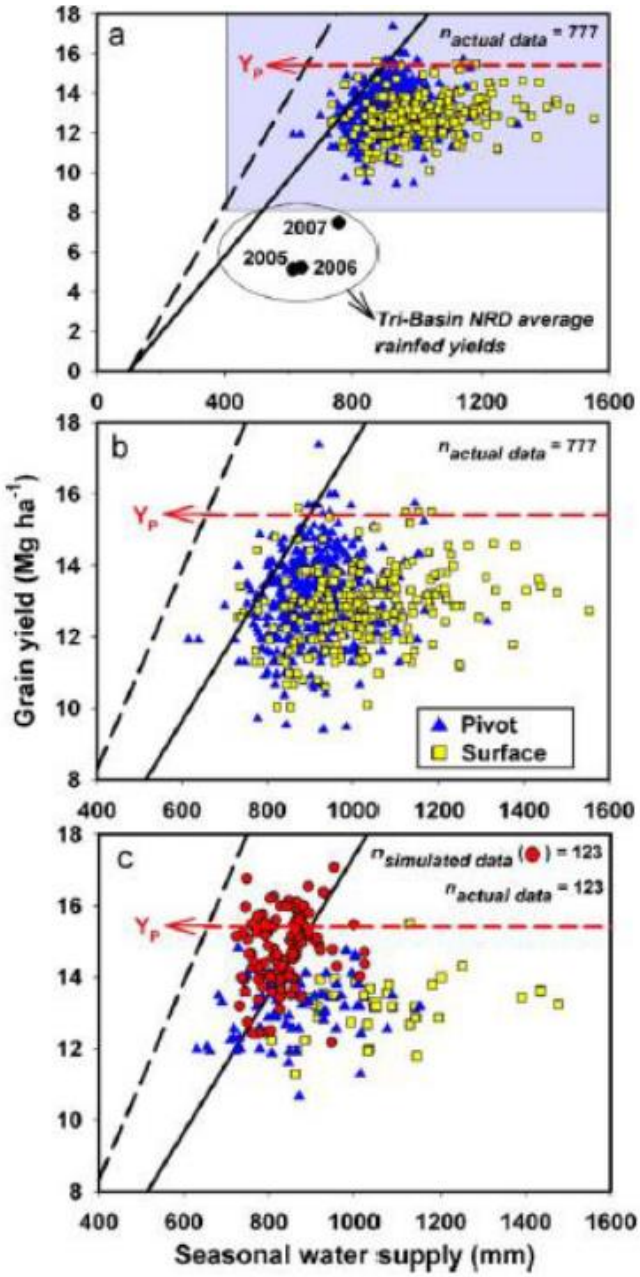


Figure 9. Relationship between:

(a) 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 (2005–2007). Data within shaded area are shown in:

(b) Disaggregated by irrigation system type, or

(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 water productivity functions from Figure 7. Note scale differences for axes in (a) versus

(b) and (c). Horizontal dashed lines indicate average simulated yield potential (Yp) with current crop management in the Tri-Basin NRD (15.4Mgha^{-1}).

From Grassini et al., 2011b.

Crop improvement to increase water use efficiency

Public and private investment in genetic crop improvement during 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 (e.g. Duvick and Cassman, 1999; Peng et al., 1999; Richards and Hall, 2013) rather than from raising the biophysical yield ceiling through improvements in photosynthesis or respiration efficiency as mentioned previously. 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. And while biotechnology and bioinformatics can help accelerate the

selection process, it has not yet been successful in giving a significant improvement in drought resistance. Indeed, current state-of-the-art genetic engineering allows manipulation of single genes and thus greatest success has come from modification of plant traits under single-gene control. Resistance to a single disease or insect pest, or resistance to an herbicide are all traits governed by a single gene. It is therefore no wonder that commercialization of transgenic (i.e. 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. Capacity to modify and improve 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 et al., 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 et al., 2014). Both programs have been underway for at least a decade. So far the single-gene approach has not resulted in release of commercial hybrids with significant improvement in drought resistance that has 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 release of hybrids with improved drought resistance (Gaffney et al., 2015). The magnitude of improvement is a modest 6.5%, which is in the range of what would be expected from a large investment in a modern, conventional, brute force approach. It is, however, an important contribution and continued incremental progress should be expected.

Summary and conclusion bullet points

- Meeting food demand while conserving natural resources is perhaps the single greatest challenge facing humankind. It requires substantial acceleration in rate of gain in crop yields on existing farm land and minimizing conversion of natural ecosystems for food production.
- While there is tremendous potential to close current yield gaps on existing farm land, doing so will not likely reduce expansion of crop production area without well-coordinated national policies regarding land use change.
- Likewise, there is enormous potential to improve water use efficiency of irrigated agriculture, but effective policies and regulations are needed to ensure that water resources are not being depleted or degraded.
- Future improvements can be expected from continued innovations in both agronomic practices and genetic improvement, although current seed company business models are in question given rush to merge for all major seed companies, and appropriate business models have yet to be developed to take full advantage of farmer-reported data on crop management, high resolution spatial data on soils and climate, as well as advances in computing power, remote sensing, communication technologies, and crop simulation models.
- There is need for increased investment in agricultural R & D coupled with much improved prioritization to increase effectiveness and efficiency of that investment. In particular, there is urgent need for ruthless focus on dual goals of accelerating crop yield gains while concomitantly reducing negative environmental impact. Unfortunately, such an explicit focus is not currently in place.

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