Increasing Crop Productivity to Meet Global Needs for Feed, Food, and Fuel

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Global demand and consumption of agricultural crops for food, feed, and fuel is increasing at a rapid pace. This demand for plant materials has been expanding for many years. However, recent increases in meat consumption in emerging economies together with accelerating use of grain for biofuel production in developed countries have placed new pressures on global grain supplies. To satisfy the growing, worldwide demand for grain, two broad options are available: (1) The area under production can be increased or (2) productivity can be improved on existing farmland. These two options are not mutually exclusive and both will be employed to produce the additional 200 million tonnes/year of corn (*Zea mays*) and wheat (*Triticum aestivum*) estimated to be needed by 2017. Both options will alter the environmental footprint of farming. Of the two options, increasing productivity on existing agricultural land is preferable as it avoids greenhouse gas emissions and the large-scale disruption of existing ecosystems associated with bringing new land into production. In the United States, breeders, agronomists, and farmers have a documented history of increasing yield. U.S. average corn yields have increased from approximately 1.6 tonnes/ha in the first third of the 20th century to today's approximately 9.5 tonnes/ha. This dramatic yield improvement is due to the development and widespread use of new farming technologies such as hybrid corn, synthetic fertilizers, and farm machinery. The introduction of biotechnology traits and development of new breeding methodology using DNA-based markers are further improving yields. Outside the United States, similar farming practices have been adopted in some agricultural nations, but in many major grain-producing countries, yields still lag well behind world averages. By continuing to develop new farming technologies and deploying of them on a global basis, demand for feed, fuel, and food can be met without the commitment of large land areas to new production.

Global demand for corn and wheat is growing at a rapid pace. As disposable incomes have risen in developing countries, meat consumption has increased. Among urban Chinese, meat consumption rose from 25 kg person^{-1} year^{-1} to 32 kg person^{-1} year^{-1} between 1996 and 2006 (von Braun, 2007). It is anticipated that meat consumption will continue to grow in developing countries because global consumption levels remain far below the approximately 100 kg person^{-1} year^{-1} meat consumption rate of the United States and many western European countries. Globally, meat consumption is expected to grow by 55 million tonnes to 310 million tonnes/year over the next decade (OECD-FAO, 2008). During this same period, biofuel production from corn and, to a lesser extent, wheat is expected to grow by 28 billion liters to 67 billion liters/year (Fig. 1). Meeting the expected demand for meat will require feed grain usage to increase by about 50 million tonnes to about 640 million tonnes/year. Concomitantly, grain consumption for biofuel production is likely to increase by about 60 million tonnes to about 145 million tonnes/year. When food use for corn and wheat is added to the calculation, total demand for corn and wheat over the next decade is expected to increase by about 15% or about 200 million tonnes/year to a total of approximately 1.5 billion tonnes/year (Table I; FAPRI, 2008).

The Food and Policy Research Institute (FAPRI) estimates that an additional 6 million ha of corn and 4 million ha of wheat plus a roughly 12% increase in global corn and wheat yields will be used to produce this additional 200 million tonnes of grain. Both increases in planted area and increases in yield are likely to be needed to meet global demand for grain. However, improving yield on existing agricultural land will have a lower environmental impact than bringing new land into production. Cultivation of new acreage requires land clearing and subsequent tillage that results in significant greenhouse gas emissions (Fargione et al., 2008) also has negative impacts upon biodiversity and water quality (Foley et al., 2005).

Increasing the productivity of existing agricultural land will also have environmental consequences (Tilman et al., 2002), but the negative consequences are generally less onerous and in some cases can be positive, depending upon how the land was previously used. Increased use of nitrogen fertilizers, a concern with both methods of increasing production, can increase nitrous oxide emissions, reduce water quality, and increase the size of hypoxic zones (Donner and Kucharik, 2008). However, incremental yield increases can be achieved on existing agricultural land through conservation tillage or transgenic insect control. Conservation tillage can decrease erosion, conserve soil

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www.plantphysiol.org/cgi/doi/10.1104/pp.108.130195

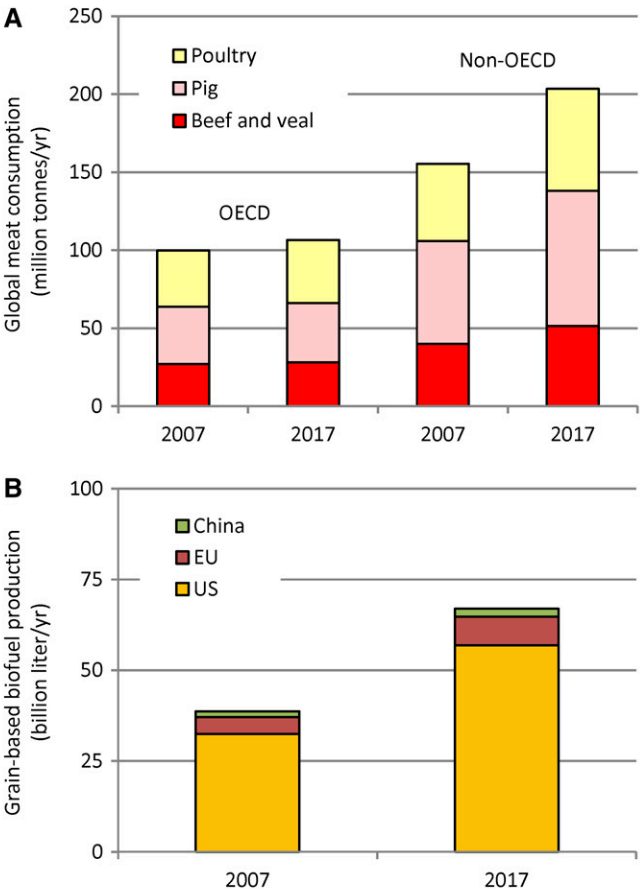

Figure 1. Estimates of global meat consumption and grain-based biofuel production. A, Global meat consumption estimates from OECD-FAO (2008). Meat consumption outside of the OECD is expected to increase by 48 million tonnes/year in the next decade. B, Global grain-based biofuel production estimates from FAPRI (2008). Grain-based biofuel production is expected to increase by 28 billion liters/year in the next decade.

moisture, and increase soil organic matter (Lal, 2004), and transgenic insect control can reduce broad spectrum insecticide use (Qaim and Zilberman, 2003; Cattaneo et al., 2006).

Global corn yields average 4.9 tonnes/ha and have been increasing steadily for many years (Fig. 2). This is encouraging, but yields in major grain-producing countries are nearly double the global average, suggesting that there is room for significant improvements in global yields. Average corn yield in the United States is 9.4 tonnes/ha and Canadian farmers attain average yields of 8.2 tonnes/ha with this crop of tropical origin. In contrast, corn yields in the 10 largest lower-yielding corn-producing countries are just 2.8 tonnes/ha (Table II; FAO, 2008), well below the global average. Much of the disparity in yields can be ascribed to agronomic practices, such as the use of open-pollinated corn varieties instead of hybrids, low input rates, or poor soil management. Brazil (29%), India (56%), and Romania (57%) all plant significant amounts of open-pollinated varieties. Weather is also a significant factor in some countries, but the use of less robust production systems can magnify the effects of unfavorable weather in countries such as South Africa and Romania. Increasing the use of modern farming practices in these countries, together with the infrastructure, marketing, and risk management tools needed to support them, could lead to significant increases in crop production that limit the need to bring incremental land into production.

Higher crop prices, prompted in part by rising demand, have increased costs for urban consumers, especially those in poorer countries. However, higher crop prices will also provide farmers with the economic incentive to invest in farming methods and technologies that improve crop yields (von Braun, 2007; Gallagher, 2008). Raising corn yields in the 10 largest, below average, corn-producing countries to just the world average will result in the production of an additional 100 million tonnes of corn or about 80% of the projected growth in demand by 2017. Implicit in this scenario is the idea that rising yields will markedly diminish the global need for new crop acreage.

Rates of gain for yield have changed as new agricultural technologies have been developed and adopted (Griliches, 1960; Troyer, 2006). Average annual corn grain yields in the United States were relatively steady at approximately 1.5 tonnes/ha prior to the 1930s. Yields began to increase when hybrid corn was first introduced and the rate of gain accelerated further in the 1950s as single cross hybrids were introduced

Table I. *Global corn and wheat production and consumption estimates from FAPRI's 2008 U.S. and World Agricultural Outlook*

All values are in million tonnes/year.

Crop	Crop Year	Production	Feed	Fuel	Food/Other
Corn	07/08	767	492	84	191
	17/18	896	528	143	225
	Increase	129	36	58	35
Wheat	07/08	603	98	1	503
	17/18	688	113	3	572
	Increase	85	14	2	68
Combined	07/08	1,370	590	85	694
	17/18	1,584	641	146	797
	Increase	214	50	60	103

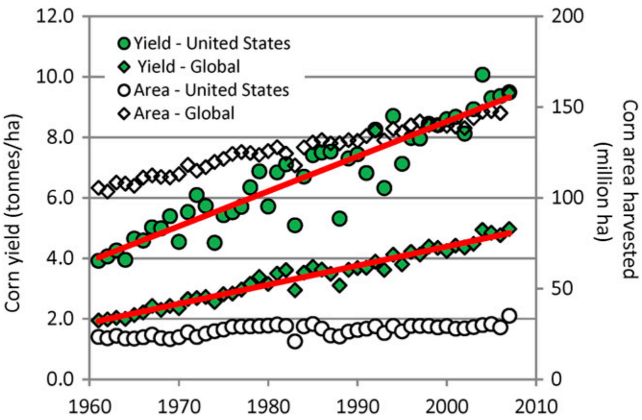

Figure 2. Annual corn yield averages and area planted in the United States and the world. Yield rate of gain in the United States from 1961 to 2007 was 0.11 tonnes ha^{-1} $year^{-1}$. Global yield rate of gain was about half of this at 0.06 tonnes ha^{-1} $year^{-1}$. Global corn area harvested has been increasing at the rate of 0.93 million ha/year. In the United States, corn area harvested increased by approximately 5 million ha in 2007 and 2008, although the long-term trend is much lower at 0.15 million ha/year (FAO, 2008). Lines indicate yield trend line.

(Troyer, 2006; Fig. 3A). Similarly, U.S. sorghum (*Sorghum bicolor*) yields increased sharply in the 1950s as hybrid sorghums were adopted (Miller and Kebede, 1984). Since that time, yield has improved steadily because of fertilizer management, the development of more efficient farm machinery, and the breeding of hybrids with improved stress tolerance that in turn enabled higher plant populations (Tollenaar and Lee, 2002) and earlier planting dates (Kucharik, 2008). Genetic gain experiments, in which hybrids that were widely grown at different points in time, often referred to as era hybrids, are compared side by side in the same trials, have been employed to estimate that about 50% of the yield gained between the introduction of hybrid corn, and today is derived from breeding and the remainder from improved agronomic practices (Duvick, 2005). Similar results have been reported from studies in France, Canada, and Brazil (Russell, 1991; Duvick, 2005). As new farming technologies are adopted by farmers, the gap between test plot results, such as those reported by Duvick, and on-farm yield averages decreases. Between 1935 and 1990 this gap shrank from about 3.0 tonnes/ha to about 1.8 tonnes/ha. However, as rates of gain derived from breeding have increased in recent years (Fig. 3B), this gap appears to have widened again. This observation supports the hypothesis that the immediate future will witness a shift in average rates of gain as newer hybrids are adopted more widely in the United States and elsewhere.

Marker-assisted breeding and biotechnology traits are relatively new technologies for the improvement of productivity. Incorporation of these technologies into crop improvement programs is likely to increase rates of gain beyond those seen in the last few decades. Results from a Monsanto Company study of a large number of commercial corn and soybean (*Glycine max*) populations indicated that use of markers can improve the rate of gain for yield and associated traits such as grain moisture and stalk lodging (Fig. 4; Eathington et al., 2007). Likewise, the suite of biotechnology traits currently used in commercial production in the United States increases average yields by protecting corn from the stress of competing pests and weeds (Fig. 5). Data

Table II. *Average corn yields from high- and low-yielding countries*

Values are 5-year averages from 2003 to 2007 (FAO, 2008). Yield, harvested area, and production were averaged independently and do not necessarily sum across this table.

Country	Area	Yield	Production
	million ha	*tonnes/ha*	*million tonnes*
High-yielding countries	64.4	7.5	482
United States	30.5	9.4	287
China	26.2	5.2	136
Argentina	2.5	6.8	17
France	1.6	8.4	14
Hungary	1.2	6.4	8
Canada	1.2	8.2	9
Italy	1.1	8.8	10
Low-yielding countries	48.0	2.8	132
Brazil	12.7	3.4	44
India	7.6	2.0	15
Mexico	7.4	2.9	21
Nigeria	3.8	1.6	6
Indonesia	3.4	3.4	12
Tanzania	2.9	1.1	3
South Africa	2.9	3.1	9
Romania	2.7	3.4	9
Philippines	2.5	2.2	6
Ukraine	1.9	3.7	7

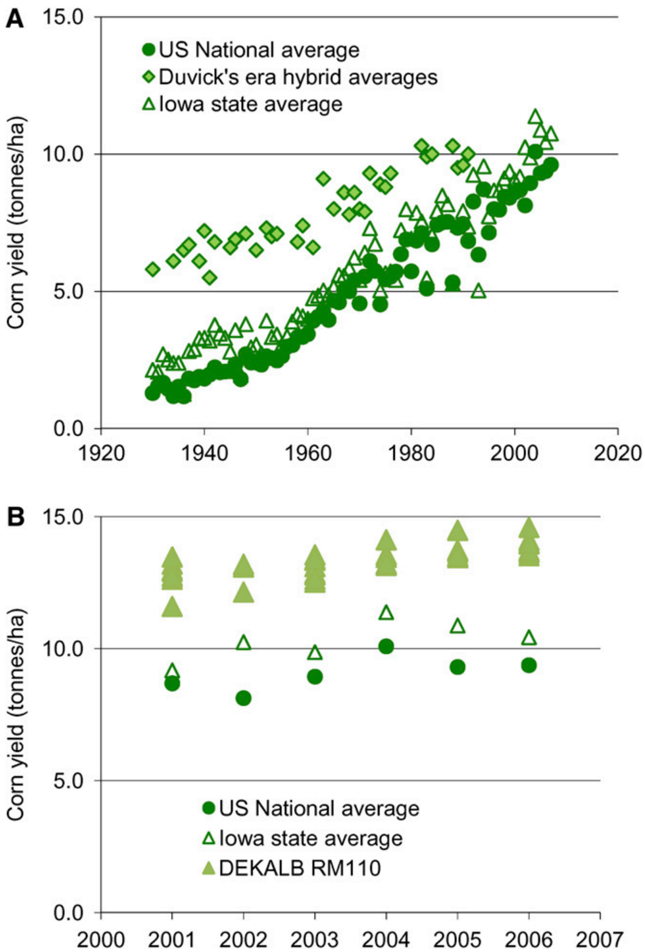

Figure 3. U.S. corn yield averages compared to yields obtained with widely used hybrids in test plots. A, National and Iowa corn yield averages (USDA ERS, 2008); Duvick's era hybrid average yields are from Duvick (1997). Iowa state averages are included as the era hybrid experiments were conducted in Iowa. The yield differential between test plots grown in Iowa and the Iowa state averages can be seen to decrease over time from approximately 3 tonnes/ha in 1936 to 1942 to approximately 1.8 tonnes/ha in 1988 to 1991. B, Genetic gain study of DEKALB commercial hybrids released from 2001 through 2006 in the 110-day relative maturity group (RM110), a region of the corn belt stretching across central Iowa. New RM110 commercial hybrids introduced from 2001 through 2006 were tested at 20 locations/year from 2005 through 2007 to produce the reported yield averages. All seed was from the same nursery and none of the hybrids contained biotechnology traits (Trevor Hohls, personal communication). Annual yield improvement was estimated at 0.24 tonnes ha^{-1} $year^{-1}$ for this group of hybrids and average yields were 3 tonnes/ha greater than Iowa and 4.2 tonnes/ha greater than the U.S. national average for this set of hybrids.

documenting the resulting reduction in risk to growers has been rigorously reviewed and acknowledged via the Federal Crop Insurance Corporation's Biotech Yield Endorsement, a risk management instrument that offers an insurance premium rate reduction for farmers using a suite of biotechnology traits (USDA FCIC, 2008). In 2008, farmers in the United States have planted 11 million ha of triple-stacked corn containing biotechnology traits that provide resistance to corn borers, corn rootworm, and the herbicide glyphosphate (Monsanto, 2008). While the yield benefits of these biotechnology traits vary from year to year, this level of planting will increase corn supply in the United States by approximately 5% if yield results seen in 2005 to 2007 are manifested in the 2008 growing season. The contribution of biotechnology traits to world corn supply will increase as they are used more widely.

The next generation of commercialized, biotechnology traits is likely to have a larger impact on crop yields. Improved drought tolerance will be one of the next major, transgenic technologies brought to the marketplace (Fig. 6; Nelson et al., 2007; Castiglioni et al., 2008). Drought tolerance has the potential to (1) increase yields in drier areas, (2) increase average yields in rain-fed systems by reducing the effects of sporadic drought, and (3) decrease water requirements in irrigated systems. Similarly, biotechnology traits that improve yield (Lundry et al., 2008) or oil concentration in soybean (Lardizabal et al., 2008) should improve global supplies of vegetable oil and protein meal. The first of these biotechnology traits, a higher-yielding, glyphosphate-tolerant soybean will be offered commercially in 2009 and commercialization of improved drought tolerance traits is expected around 2012. The transgenes described above are at relatively advanced stages of commercial development. A larger collection of transgenes derived from large-scale screening programs such as those described by Riechmann et al. (2000), Van Camp (2005), and Creelman et al. (2008) are at earlier stages of development. Biotechnology traits that improve grain yield and nitrogen use efficiency in replicated multiyear field trials are expected to reach farmers' fields in the second half of the next decade (Padgette, 2008).

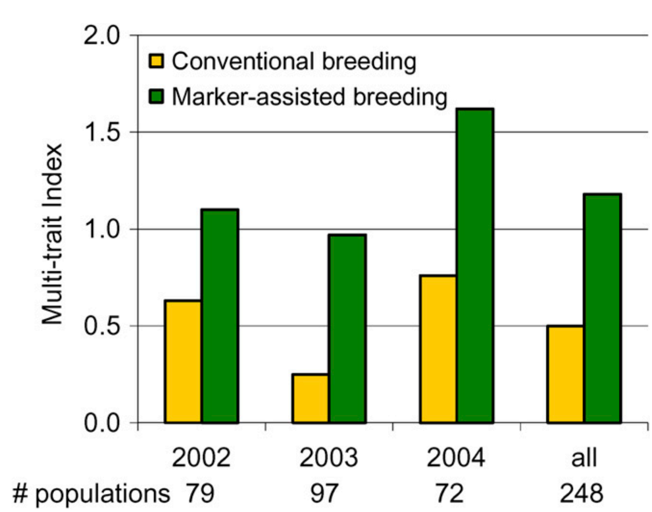

Figure 4. Breeding rates of gain for a multitrait index for 248 corn populations initiated across 3 years. The multitrait index is weighted toward yield, but also incorporates other agronomic traits such as grain moisture and stalk strength (Eathington et al., 2007).

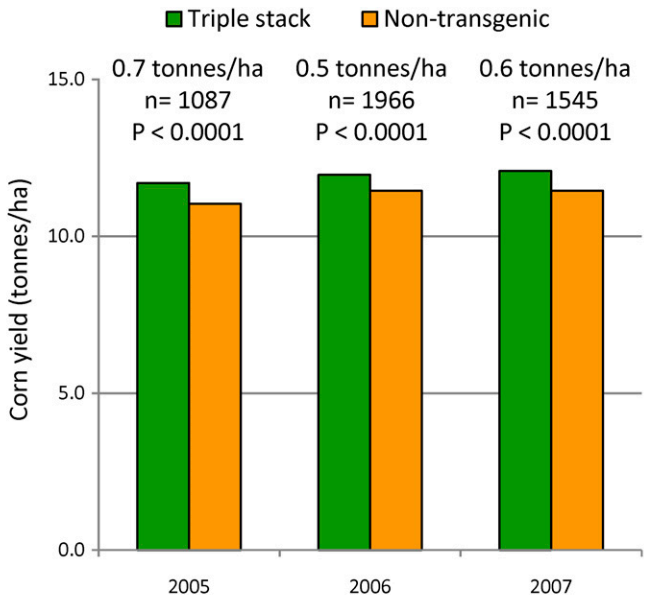

Figure 5. Yield advantage of triple-stack corn. Corn hybrids expressing either three biotechnology traits (YieldGard Plus with Roundup Ready Corn2 or YieldGard VT Triple) or without any biotechnology traits were tested in yield trials at the indicated number of locations across the United States in 2005, 2006, and 2007. Average yield values are shown in the bars and the yield difference between triple-stack and non-transgenic corn is indicated in the text above the bars. These are average values from yield trials run across corn-growing regions in the United States. Values can be significantly higher in regions with more insect pressure. Nontransgenic corn was treated with insecticide to control corn rootworm.

This group of genetically identified biotechnology traits are referred to as yield-enhancing traits, but the increase in yield may be due to an increase in yield potential and/or an improvement in tolerance to one or more stresses. Collectively, the next generation of biotechnology traits should contribute significantly to productivity on existing cropland, thereby increasing grain supplies and reduce the need to bring new land into production.

While breeders, agronomists, and farmers are working to increase yields, a number of factors that may reduce yields must be considered. Over the next two decades, climate change effects in the central United States are predicted to increase night air temperatures, the number and severity of adverse weather events, and increase the incidence of insect pests and disease. The result could be a drag on crop yields (Hatfield et al., 2008). Rapid adaptation of crops to changing climatic conditions may help mitigate these effects. Such rapid adaptation may occur for crops supported by strong breeding programs that continuously develop and introduce superior, locally adapted hybrids and varieties. New, higher-yielding hybrids produced from Monsanto's North American corn breeding program currently have a product half-life of approximately 4 years and are completely turned over about every 7 years, raising hopes that, for corn and possibly soybean, new varieties adapted to local conditions will be produced as a part of the ongoing breeding program. Unfortunately, this is not the case for crops such as wheat and rice (*Oryza sativa*) that lack the support of large, private breeding programs. Accordingly, increased public support for crop improvement efforts are sorely needed if new wheat and rice varieties are to be adapted to changing local climatic conditions. This is particularly true for regions of the world predicted to undergo more dramatic near term changes in climate than the central United States.

Nitrogen is another factor that may limit crop yields. Nitrogen may become less available as the cost of fertilizer rises and the continued growth of eutrophic dead zones and nitrous oxide emissions leads to changes in the way fertilizer is used (Donner and Kucharik, 2008). Nitrogen use efficiency, defined as the amount of crop produced per unit of input, has steadily improved in the United States since the 1980s (Frink et al., 1999). More precise nitrogen applications and genetic improvements in crops are likely to sustain improvements in nitrogen use efficiency although there is a limit to how far nitrogen application can be reduced. A 10 tonnes/ha corn crop contains around 100 kg nitrogen/ha as protein and at least this amount of nitrogen must be added back to the field to maintain fertility. Lastly, a sharp downturn in the global economy could restrict demand for both meat and fuel in ways that reduce the economic incentive to increase crop yields (IMF, 2008).

The combination of marker-assisted breeding, biotechnology traits, and continued advances in agro-

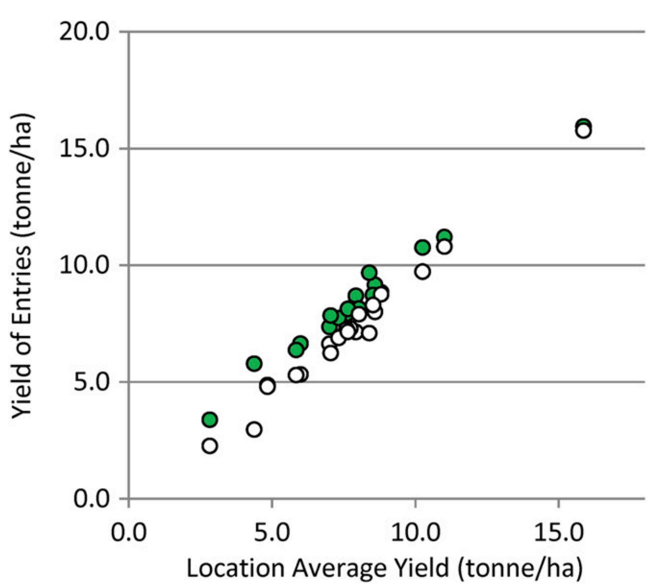

Figure 6. Yield increase in corn plants expressing cspB, a cold shock protein from *Bacillus subtilis*. Hybrids from a single transgenic event were tested in yield trials over 3 years at managed stress locations. Yield of the transgenic hybrid (green circles) and nontransgenic isogenic hybrids (white circles) at individual locations are plotted against the yield of all entries tested at that location (Castiglioni et al., 2008).

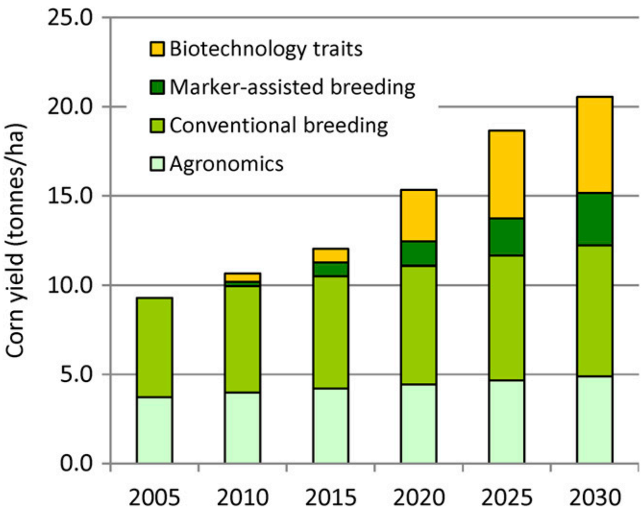

Figure 7. Anticipated impact of improvements in agronomics, breeding, and biotechnology on average corn yields in the United States. Rate of yield improvement due to breeding is extrapolated from observations such as those shown in Figure 3B, using data extending across maturity groups from Monsanto's North American corn breeding program. Agronomic (planting density, fertilizer use efficiency, improvements in soil management) contributions to the rate of yield improvement are considered to proceed at current historical rates based on estimates in Duvick (2005). Rate of yield improvement for biotechnology traits is a combination of the effects of current yield-protecting biotechnology traits, the introduction of biotechnology traits for drought tolerance, and additional yield-enhancing biotechnology traits. Biotechnology contributions to yield from herbicide tolerance, corn borer, and corn rootworm protection are estimated from the data presented in Figure 5. Biotechnology contributions to yield from drought tolerance are estimated from data presented in Figure 6 and an assumption that drought conditions strong enough to reduce yield will be seen on approximately 10% of the planted acres. Biotechnology contributions from yield-enhancing transgenes assume the introduction of three new biotechnology traits with effects similar to those described by Padgette (2008) over the course of the next decade. In each case biotechnology trait adoption curves such as those observed for current commercially available biotechnology traits are assumed (Monsanto, 2008).

nomic practices has the potential to double corn yields in the United States over the next two decades (Fig. 7). Doubling U.S. average yields would raise average yields to approximately 20 tonnes/ha, values now seen rarely in nonirrigated corn. The theoretical light-limited maximum for corn yields in the United States has been estimated at approximately 25 tonnes/ha (Specht et al., 1999; Tollenaar and Lee, 2002), close to the 24.2 tonnes/ha recorded on a 2-ha plot by David Hula of Charles City, Virginia in the 2007 National Corn Growers Association Corn Yield Contest. This fact suggests that corn yields can be doubled without large increases in yield potential, although significant improvements in broad stress tolerance, water use efficiency, and broad dissemination of excellent agronomic practices will be required to approach the Hula yield on broad acreage. Improving yields in corn and other crops on a global basis will allow farmers to meet global demand for feed, fuel, and food while minimizing the need to bring large amounts of new land into crop production. Even if crop producers supported by the agricultural sector fall short of doubling yields, continued public and private investment in agricultural technology will lead to significant increases in productivity that will help supply the world's needs for food, meat, and energy in a sustainable fashion.

ACKNOWLEDGMENTS

Many colleagues at Monsanto have contributed to this review. John Anderson, Marsha Stanton, Beth Calabotta, Dusty Post, Trevor Hohls, and Paolo Castiglioni have all provided data, helpful suggestions on content, or editing. In addition, a much larger group of people have contributed to the research and development that has made the inventions described in this review possible.

Received September 22, 2008; accepted October 28, 2008; published January 7, 2009.

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