Can we feed the world in 2050?

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Abstract
Because the expansion of cropped areas is ultimately limited and increasingly undesirable, we review recent progress in maize, wheat, rice and soybean yields resulting from improved varieties and agronomic practices. Over the past 20 years (yr) farm yields (FY) of maize have increased linearly with time at 1.6% per annum, versus 1.2% for soybean and 1% for wheat and rice. However, relative rates of increase have fallen in rice and wheat over time. The yield gap between FY and potential yield (PY), expressed relative to FY, ranges from 30 to 200%, and is generally larger in developing countries. Efficient irrigation practices, improved pest control, increased fertility and exploitation of variety x management interactions can narrow this gap and increase factor productivity. The development of higher-yielding stable varieties increases this exploitable yield gap, but cost per unit gain is rising. Increases in PY depend on increased biomass through improved radiation-use efficiency and high but stable harvest index, especially under water-stressed conditions. Research on heterosis, molecular breeding and transgenics suggest that rates of gain from genetic sources could be increased by at least 50%, the rate needed to generate a 70% rise in production of staples by 2050 without major increases in food prices. This requires a sharp boost in research investment in plant agriculture from public and private sources, accompanied by facilitating policies. The time to start is now.
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Introduction
Mark Twain noted that "prophecy is a good line of business, but it is full of risks". Broad trends affecting crops provide guidelines to projections over the next 40 yr. Firstly, real prices on global grain markets will be higher than the 2000-2007 average because of water, land and energy shortages, climate change, and increased demand for food, fuel and feed. Secondly, area expansion will be relatively small, and in some cases will place crops in increasingly marginal environments, so increases in yield and yield stability are critically important. This paper focuses mainly on the three main cereals, rice, wheat and maize – crops that provide 50% of the calories consumed and occupy 58% of the annual crop area. Yields in all cereals have increased at 42.4 kg/ha/yr in the 20 yr from 1989-2008 (FAOSTAT 2010) and 44 kg/ha/yr from 1961-2008. Soybean, as the most important global grain legume, is also considered. It is noteworthy that yield increases of all four crops have been linear with time in the 1989-2008 period, with gains in maize (77 kg/ha/yr) significantly exceeding those of the other three, and rice (39 kg/ha/yr) exceeding that of wheat and soybeans (both 28 kg/ha/yr). Linear increases in yield imply a reduction in the relative rate of yield increase, and from 1961 to 2008 the relative increase in cereal yields has fallen from 3.1% to 1.25% annually.

Throughout this paper we refer to farm yield (FY), taken as average grain yield as reported in FAOSTAT (2010); attainable yield (AY), or that obtained by a skilful farmer with normal regard to economics and risk; and potential yield (PY), or the yield of the best adapted cultivar grown under non-limiting inputs except those not readily changed by a manager (e.g. temperature, soil texture). PY is usually determined from well-run yield trials or from simulation studies of modern cultivars where water is not limited, but water-limited potential yield (PYW) is becoming increasingly important.

Global food demand
Global population growth rate is falling. During 2010, when population is expected to exceed 6.9 billion (bn), global population will grow by 80 m people or 1.15%. By 2050 population is projected to be 9.15 bn, and growing at around 35 m (0.4%) per annum (United Nations 2010). Comparing the present proportions of global population with projections in 2050 by regions, there will be an increase in Africa's share from 15% to 22%, a fall in Asia from 60% to 57%, and a decline in Europe from 11% to 8%, while Oceania remains steady at around 0.5%. If it is assumed that the linear increase in yields will continue unabated till 2050, the projected growth rate of population is similar or lower than the rate of increase of cereal yields (Table 1). However, as incomes rise there is a change in dietary preferences from cereals towards meat consumption,

with an attendant decline in conversion efficiency. This change results in an increased demand for cereals as feed grains, so demand for grains will increase at a greater rate than that of the population. Use of grains for biofuels is rising, and Rosegrant *et al.* (2008) suggest that by 2020 industrial countries could consume 150 kg maize/capita/yr for ethanol production - similar to rates of cereal food consumption in developing countries.

How much extra grain do we need?

Tweeten & Thompson (2008) assume linear growth in yields of major cereals and project a 79% increase in demand for all foods in 2050 over 2000 levels versus an increase in supply of 57% (71% for cereals). This change will result in a 44% increase in prices in real terms over 2000 levels. They conclude that global farm output will need to almost double in the first half of this century to maintain historic trends in real prices for food. A recent estimate by IFPRI (Rosegrant *et al.* 2008) accounts for income growth, biofuel and feed requirements, and projects an overall increase in demand of 56% in cereals in the 2000-2050 period. They assume average annual yield gains in wheat of 1%, rice 0.7% and maize 0.9% per annum, and foresee real price increases of 91% of wheat, 60% for rice and 97% for maize from 2000 to 2050. If annual yield growth in cereals could be increased from 1% to 1.43% annually, Rosegrant *et al.* forecast that these draconian price rises could be avoided. In summary, the linear increases in yields that have occurred over the past 50 yr are not sufficient for the next 40 yr, and a 43% increase in relative gain per annum in cereal yields is needed to avoid food price increases. Comparing a 1.43% annual growth in yield vs. the historic rate of 44 kg/ha/yr would, by 2050, result in FYs of 6.3 t/ha versus 5.3 t/ha, and 84% versus 56% more grain. Other considerations are the needs in some countries to reduce the per capita intake of food and to reduce food wastage. These factors should help align food demand and supply.

Prospects for expanded crop area

Although there are good prospects for added crop area in Brazil, Eastern Europe and in sub-Saharan Africa (SSA) (Tweeten & Thompson 2008), elsewhere there is little possibility except at the cost of grazing lands that are often marginal for cropping. Annual changes in cereal area 1989-2008 have been negative overall (-0.18%) and by crop are maize (+0.8%), rice (+0.3%), wheat (-0.3%) and soybean (+2.5%), with larger percent losses for sorghum and millets (FAOSTAT 2010). Expansion of cropped areas through development of large commercial farms has recently occurred in SSA, Brazil and Eastern Europe, sometimes at the expense of the rights of local farmers (World Bank 2010). The longer-term solution to increased production undoubtedly lies in increasing yields and improving total factor productivity. However, land expansion will continue to be important in Africa and Latin America.

Table 1 Projected annual change in population and cereal yield (latter based on past linear trends). Percentages are calculated from predicted means for that year. (Sources: FAOSTAT 2010; UN 2010).

Year	2010	2020	2030	2040	2050
% annual increase in yield	1.24	1.10	0.99	0.90	0.83
% annual increase in population	1.15	0.88	0.67	0.50	0.35

Sources of yield gains in major production areas and in key crops

We consider global trends in FY, then focus on a subsample of key production areas that offer some estimates of PY over time. Percent gain in PY and yield gaps are always expressed relative to FY levels.

Maize

Yields increased at 1.9%/yr in 1961-88, falling to 1.6%/yr in 1989-2008. Increases in FY over the past 20 yrs of the largest producers, USA, China and Brazil are 1.5%, 0.9% and 2.7% per annum (Table 2).

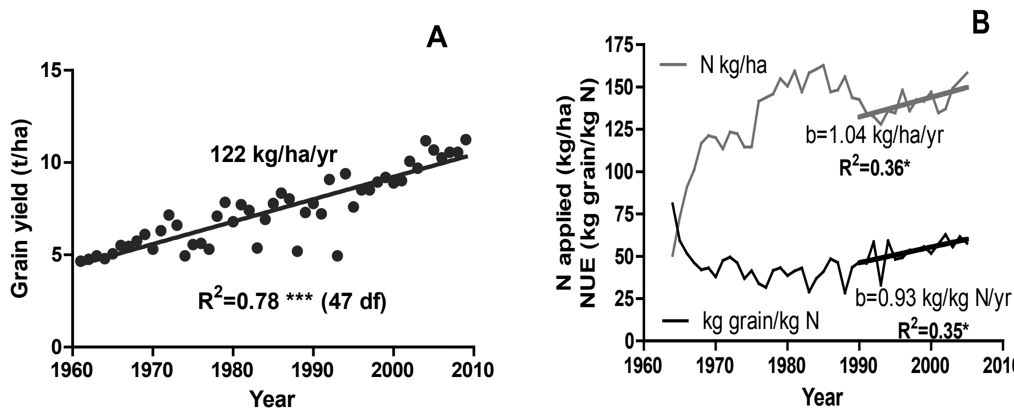
Case study: *Iowa, USA:* Iowa grows 5 m ha of maize annually in a maize-soybean rotation. Increases in FY since 1961 (Fig. 1A) were 5% greater than the average for the US. Gains in Iowa have been especially high since 1995, averaging 224 kg/ha/yr over this 15 year period - a gain that is significantly greater (P=0.02) than the 92 kg/ha/yr for the 1961-1994 period. This reflects better weather, precision farming, and the use of stress tolerant GM hybrids. It also reflects earlier planting (Kucharik 2008) made possible with cold-tolerant hybrids, reduced tillage and large-scale precision planting machinery. Irrigated land area in Iowa is small and has barely altered. Modern hybrids are more stable under insect attack, density and drought stresses, and plant density on farm has been rising at around 1 000 plants /ha/yr. PY is thought to be around 15-18 t/ha in the US Midwest (Grassini *et al.* 2009; NCGA 2010), or 40-70% above FY in Iowa. Older studies suggest that around 50% of the yield improvements in FY are due to improvements in agronomy and 50% to improved genetics that exploits hybrid x management interactions (Duvick 2005). As yield levels increase, however, the proportion of gain attributable to improved genetics appears to be steadily rising.

Other maize growing countries: Second- and third-largest producers of maize globally are China and

Table 2 Maize production and annual gains in FY from 1961-1988 and 1989-2008, relative to mean yields in the last 2 years of the period considered. Source: FAOSTAT 2010.

	USA	China	Brazil	Kenya	Australia	New Zealand	World
Production 2006-8 (m t)	302.0	156.7	51.3	2.8	0.33	0.21	772.4
Gain 1961-88 (kg/ha/yr)	110	70	24	26	57	172	65
%/yr	1.6	1.4	1.3	1.4	1.6	1.9	1.9
Gain 1989-08 (kg/ha/yr)	140	48	100	-8	66	120	77
%/yr	1.5	0.9	2.7	-0.5	1.3	1.1	1.6

Figure 1 A: Maize grain yield versus year of harvest for the state of Iowa; B: N application and nitrogen use efficiency (NUE) versus year of application (see Fischer & Edmeades 2010).



Brazil, where rates of gain in FY over the past 20 yr have been 48 (0.9%) and 100 kg/ha (2.7%) /yr. Annual gains in FY for maize over the same period in Australia and New Zealand have been 66 kg/ka (1.3%) and 120 kg/ha (1.1%), respectively. Competition-winning yields in New Zealand (GTL pers. comm. 2009) over the past 5 yr have averaged 16.5 t/ha, or 47% greater than average FY. In parts of the developing world where maize is a staple, levels of FY are often low, especially in Mesoamerica (2.9-3.2 t/ha) and sub-Saharan Africa (1.0-2.5 t/ha). Potential yield is also lower in the tropics, especially in the lowlands, but is rarely less than 6 t/ha, and in the middle elevations can often reach 12 t/ha. The yield gap is therefore > 200% of FY levels. Gains in FY in sub-Saharan Africa in the past 20 yr have been low, ranging from 0 in eastern Africa to 32 (1.9%) and 69 kg/ha (2.2%)/yr in western and southern Africa - though these estimates are sensitive to the time period considered. Lack of improvements in maize yield in eastern Africa, where population is increasing at 2.3% annually, is of major concern.

In summary, current global maize yield increases of 1.6% annually are able to keep pace with projected population and demand increases from income growth, and there remains a gap of 30-200% between FY and PY that certainly can be narrowed. However, there is some evidence that the absolute rate of increase in FY in the US is greater than the rate of increase in PY.

Wheat

The global rate of FY increase has declined from 45 kg/ha (2.0%)/yr in 1961-88 to 28 kg/ha (1.0%)/yr in 1989-2008 (Table 3).

Case studies in wheat: Well-documented cases of historical FY and PY values are available from the Yaqui Valley in NW Mexico and from the United Kingdom. PY estimates are 63% greater than FY in Yaqui, and 33% greater than FY in UK (Fig. 2). In the Yaqui Valley, typifying irrigated wheat production in the subtropics, there are high rates of N application and variety turnover, yet the rate of increase has slowed compared with the 1950-75 period (Fig. 2A). When corrected for a consistent decline in mean temperatures, gains in FY fall to 0.3% per annum, despite CIMMYT's breeding presence in the valley.

The UK has a high average wheat yield (7.8 t/ha), and typifies rainfed winter wheat production. Yields have increased annually at 0.7% (FY) and 0.8% (PY), and the yield gap is steady at around 30% of FY. Yield increases in the UK have declined from107 kg/ha/yr in 1961-1988 to 51 kg/ha/yr since 1989, despite an active public and private breeding effort. Rates of increase, actual and percent, are falling for the main wheat-growing nations (Table 3). New Zealand, with 0.05% of

Table 3 Wheat production and annual gains in FY from 1961-1988 and 1989-2008, relative to mean yields in the last 2 years of the period considered. Source: FAOSTAT 2010.

	China	India	USA	Russia	Australia	UK	NZ	World
Production 2006-8 (m t)	110.1	74.6	57.8	52.7	15.1	15.1	0.3	635.4
Gain 1961-88 (kg/ha/yr)	94	47	32	-	10	107	44	45
%/yr	1.7	2.5	1.4	-	0.7	1.4	1.1	2.0
Gain 1989-08 (kg/ha/yr)	79	28	24	38	-13	51	201	28
%/yr	3.1	1.0	0.9	1.8	-1.1	0.7	2.7	1.0

Figure 2 Changes in the FY and PY of wheat vs. time in (A) the Yaqui Valley of Mexico, and (B) in the United Kingdom. Within (A) or (B) the fitted regressions for FY and PY do not differ in slope. PY estimates are from protected variety trials (after Fischer et al. 2009).

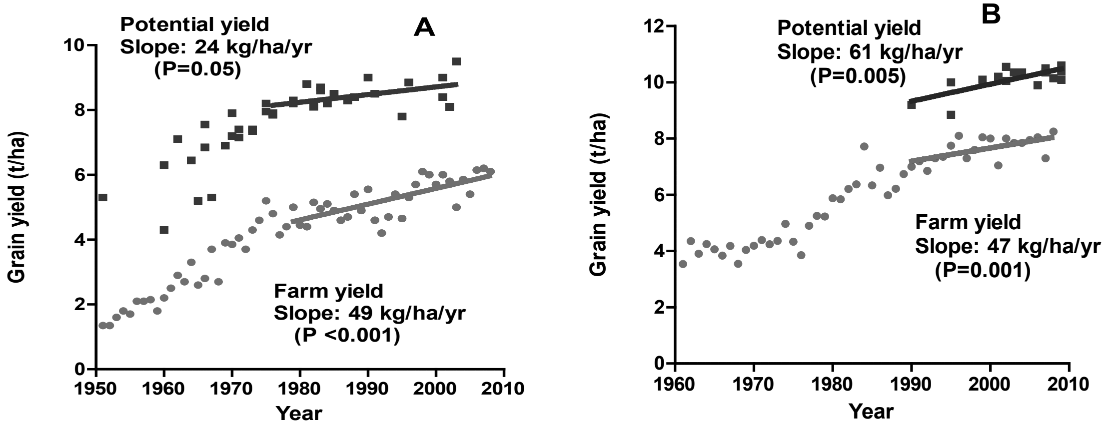


Table 4 Rice production and annual gains in FY from 1961-1988 and 1989-2008, relative to mean yields in the last 2 years of the period considered. Source: FAOSTAT 2010.

	China	India	Indonesia	Vietnam	Thailand	Bangladesh	World
Production 2006-8 (m t)	188.0	144.0	57.3	36.8	30.7	43.0	661.2
Gain 1961-88 (kg/ha/yr)	115	34	99	33	11	24	54
%/yr	2.2	1.5	2.5	1.2	0.5	1.1	1.6
Gain 1989-08 (kg/ha/yr)	42	35	23	113	51	86	39
%/yr	0.7	1.1	0.5	2.3	1.7	2.2	0.9

global production, is an exception, and a world record yield of 15.6 t/ha (or 100% of FY) has been reported from Southland (FAR 2010). Australian data are flat, with droughts reducing yield in recent years. Fischer *et al.* (2009) noted that the PY-FY gap in most wheat-growing megaenvironments in the world ranges from 25-50% of FY, but that at present rates of change this yield gap would close in the next 40-50 yr.

Rice

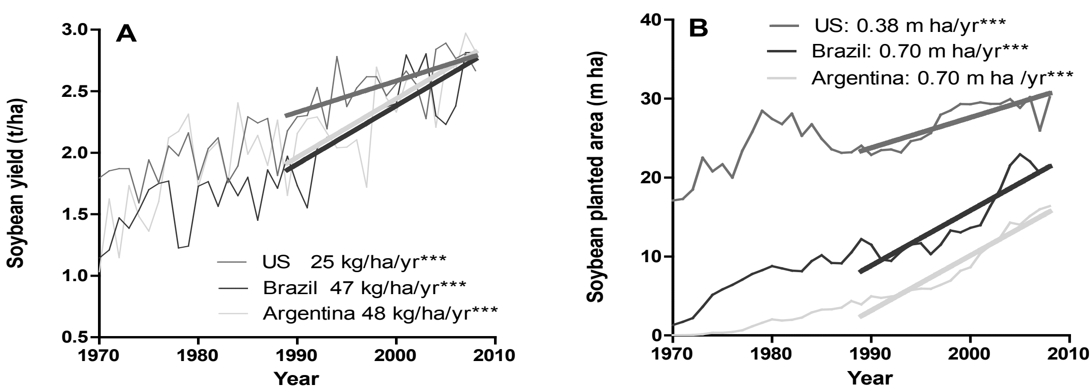
The global rate of increase in FY has declined from 54 kg/ha (1.6%)/yr in 1961-88 to 39 kg/ha (0.9%)/yr in 1989-2008 (Table 4). The PY of rice stagnated after an initial 30-40% increase in the 1960s arising from semi-dwarf varieties such as IR8, and again after a 15% boost from hybrids (Peng *et al.* 2008).

Case studies in rice: Among temperate rice producers Japan has a high mean FY (6.4 t/ha) and a long history of rice research. Japan's rate of yield increase has fallen from 41 kg/ha/yr in 1961-1988 to 27 in the past 20 yr. PY appeared to increase from 8 t/ha in 1960 to around 12 t/ha in 1990 at a rate exceeding 100 kg/ha/yr for that period. No PY data have been published since, but assuming these PY values are valid today (see Fischer & Edmeades 2009) the PY-FY yield gap is around 80%. The rate of increase in FY in China with a mean yield of 6.4 t/ha, has also declined in recent years (Table 3) despite the spread of hybrids to 60% of its area. A new generation of "super" hybrids had a PY of around 12 t/ha in 2005. This potential is projected to increase by 150 kg/ha/yr to 13.5 t/ha by 2015 when it will be 80% above expected FY levels (Peng *et al.* 2008). Super

Table 5 Soybean production and annual gains in FY from 1961-1988 and 1989-2008, relative to mean yields in the last 2 years of the period considered. Source: FAOSTAT 2010.

	USA	Brazil	Argentina	China	India	World
Production 2006-8 (m t)	79.0	56.7	44.8	14.6	9.6	222.9
Gain 1961-88 (kg/ha/yr)	19	31	51	25	14	26
%/yr	0.9	1.8	2.4	1.7	2.1	1.5
Gain 1989-08 (kg/ha/yr)	25	47	48	14	8	28
%/yr	0.9	1.8	1.7	0.8	0.7	1.2

Figure 3 Soybean yield (A) and planted area (B) versus year for USA, Brazil and Argentina. Fitted lines to 1989-2008 data are significantly different in slope for planted area but not for yield. Source: FAOSTAT 2010.



hybrids are generated using marker-assisted selection (MAS) to identify heterotic *indica* and *japonica* elements, plus other desired attributes in the inbred parents. Water constraints have led to the demise of the rice industry in Australia. Results from leading rice producing countries are mixed, but generally show more consistent gains than for wheat (Table 4). Since rice varieties have generally become earlier, when annual gains are calculated on a per day basis they are10-15% greater than those reported by FAOSTAT. Of concern are the very low yields (1.8 t/ha) in SSA where demand is rising at 6%/yr and imports comprise 50% of the world's traded rice.

Soybean

The rates of FY increase in the United States and Brazil have stayed steady in relative terms in the 1961-1988 versus 1989-2008 periods (Table 5), though rates have declined in China and India. The increase in soybean area in Brazil and Argentina has been striking, with more than 1.4 million ha of soybean area being added annually in the 1989-2008 period (Fig. 3). Farm yields in the US, Brazil and Argentina are 2.7-2.8 t/ha. Potential yields have usually been estimated from irrigated yield competitions in the US. These range in the 7-10 t/ha range (www.pioneer.com), though Specht *et al.* (1999) suggested that 8 t/ha is a biological upper limit for the crop. The PY-FY gap in the US appears to be 70-100% for this crop using the more realistic estimates of PY from University trials. Gains in FY remain around 1.2% per annum, but are impressive given the rapid expansion in soybean area in the past 10-15 years.

Summary of yield progress over crops: Recent FY gains have been around 1% per annum for rice and wheat, and greater than 1% in maize and soybean. Only maize has recorded a relative yield increase greater than the 1.43% /yr thought to be required to maintain food prices at present levels (Rosegrant *et al.* 2008). Recent gains in FY are disappointing in China and India, and are totally inadequate in sub-Saharan Africa. The relatively large gains observed in maize (and soybeans to a lesser degree) reflect the level of investment in crop improvement in maize, to the tune of around US$3 m per day by the leading private seed companies. Investments are considerably less for rice and wheat, and gains in these crops are further constrained by the need to breed for quality and to maintain disease resistance.

Filling gaps between farm and attainable or potential yields

Yield gaps between FY and AY exist because known technologies are not being applied, while the AY-PY gap exists because for some technologies adoption is either too risky or uneconomic at present. On a global scale the largest proportion of the FY-PY gap is due to drought, hence the need to consider PY_W as a special case. There is empirical evidence that FY approaches AY when markets, infrastructure and technology transfer are of a high standard, but an AY-PY gap of 25% of FY may be the economically optimal level for AY (Lobell *et al.* 2009). Institutions and infrastructure are also responsible for yield gaps, e.g., lack of farm electricity, an absence of roads and markets, or policies that reduce AY. Of the case studies considered it is only for wheat in the UK where FY is approaching this limit. Areas where large FY-AY gaps exist are sub-Saharan Africa for all major crops, where yields are constrained by infertility, weeds and water stress, themselves reflections of poor infrastructure. Here gap filling is a much higher priority than raising PY. Gap closing will be largely through smarter management of water, N, planting dates, conservation tillage and the use of stress-tolerant varieties, and will depend on technology generation and transfer. Gaps however, persist, suggesting that FY and PY need to rise in concert.

Increasing potential yield

In its simplest terms PY is the product of intercepted radiation, radiation use efficiency (RUE) and harvest index (HI). In all crops increased biomass production is usually associated with increased PY through increased grain number/m^2. This can result from improved radiation interception through delayed senescence, rapid leaf area expansion, good weed control and correct spacing, or through increased RUE. While new agronomic technologies will always play an essential part in lifting yields, management x variety interactions may be the main area for impact of agronomic research, e.g., the use of glyphosate-resistant maize or soybeans under conservation tillage that permits earlier planting and the use of longer-duration varieties. These combinations have played a key role in the exceptional yield increases recorded in these two crops in the US, Brazil and Argentina.

There is a growing conviction, however, that genetic improvement in crops will account for a greater proportion of the needed yield increases than in the past, and especially in boosting PY. The following areas are of special importance:

Stable or increased HI: Typical values of HI in improved varieties are 0.5-0.55 for winter wheat, rice, soybean and temperate maize varieties. HI is 0.4-0.45 for spring wheat and modern tropical maize varieties, suggesting a 10-20% yield improvement from improved partitioning to grain resulting in increased grains/m^2, a trait highly correlated with yield in almost all crops.

Increased RUE: Increased CO_2 concentration is lifting RUE and FY by about 0.3% per annum in C_3 crops (Tubiello *et al.* 2007), and is usually not taken into account. C_4 crops such as maize have a greater RUE than C_3 crops from 18-35°C, maximum values being 1.9-2.7 g/MJ for C_3 crops vs. 3.3-3.8 g/MJ for maize, with theoretical upper limits of 5.8 (C_3) and 6.9 g/MJ (C_4) (Long *et al.* 2006). Future increases in RUE are likely to be linked to an increased maximum rate of leaf photosynthesis (P_{max}), and improved photosynthetic rate at lower leaf irradiance. Attention is being given to the engineering of rubisco and rubisco activase enzymes by gene shuffling to improve their efficiencies. A second area of focus is to develop C_4 versions of rice and wheat, an ambitious project underway at IRRI and being considered by CIMMYT. If successful, this focus could give a 50% increase in PY of rice. Long *et al.* (2006) predict gains in RUE of 1-4%/yr through these types of mechanisms.

Exploiting heterosis: Heterosis is often considered a form of stress tolerance, and frequently has greater effects on PY_W than on PY. Hybrids account for 70% of the maize area and 10% of the rice area, but are not used in wheat or soybeans. The limitations of hybrids for rice and wheat are high seeding rates, poor yields of female parents and modest levels of heterosis. We anticipate that the inadequate seed yields and heterosis will be considerably improved over the next 20-30 yr giving a one-off yield benefit of 10%, 8% and 5% in wheat, rice and maize, respectively. A viable hybrid seed system will also attract considerable additional private sector investment in rice and wheat genetics - a key driver of accelerated genetic gain.

Water-limited production and PY_W: Water will be an increasing limitation for staple crop production over the next 40 yr. PY_W can be considered the product of transpiration (T), transpiration efficiency (TE) and HI (Passioura 1977). A goal of agronomists is to increase T by reducing evaporative and drainage losses, and increasing TE by timing growth to coincide with cooler weather. By screening segregating populations under managed water stress, breeders have increased T by selecting for deeper roots, for increased RUE by selecting for staygreen, and for increased HI. Gains in PY_W of 25-40% over the next 40 yr appear feasible in the crops considered (Fischer *et al.* 2009), and could be significantly greater if C_4 rice and wheat are successfully developed. As well, there will be a considerable spill-over benefit of improved PY into PY_W.

Transgenic crops: These were grown on 85% of maize and 95% of the soybean areas in the US in 2009 (NCGA 2010). However, GM approaches to increased PY have not resulted in commercial products to date. Most transgenic efforts are currently focused on C_4 rice and wheat, or on modifications to rubisco or activase to increase P_{max}. Increased pest tolerance derived from transgenic sources where pest control was previously inadequate (e.g., in maize and cotton), increases FY and may reduce the need for maintenance breeding. In 2012, Monsanto will launch commercial maize hybrids carrying the cold-shock protein gene *cspA* from *Bacillus subtilis* that lifts yields by 6-10% percent under moderate to severe drought (Castiglioni *et al.* 2008). This same event is being offered to five countries in SSA on a royalty-free basis. There is a reasonable probability that GM technology will result in step changes that boost PY and PY_W, provided the costs of intellectual property and deregulation can be contained, and provided there is sustained financial support for transgenic research.

Molecular breeding technologies: these offer real hope of accelerated progress in FY and PY, mainly through marker-assisted selection (MAS), marker-assisted recurrent selection (MARS), genome-wide selection and transgenics that can all be integrated with conventional pedigree breeding. Early MARS studies using whole-genome selection have led to a doubling of genetic gain (Edgerton 2009).

Credible yield projections: Specht *et al.* (1999) predicted that FY of soybeans in the US could rise to 3.6-5.6 t/ha by 2050 depending on whether yield increases follow a linear or exponential path. Yields of rice of 13 t/ha and as much as 19 t/ha for wheat look possible (see Fischer *et al.* 2009) Monsanto has set a goal of doubling maize yields in the US between 2000 and 2030 by increasing annual gains to 2.5 times the historical rate (www.monsanto.mediaroom.com). Their projections suggest that by 2030 a 20.5 t/ha national average maize yield in the US will result from improvements in agronomy (25%), conventional breeding (35%), MAS (15%) and transgenic traits (25%). Results from the average of the first three places in US maize yield competitions 2006-2008 show yields of 17.8 t/ha (rainfed; n=60) and 20.3 t/ha (irrigated; n=36) (NCGA 2010), suggesting such yields are possible. In this era of sequencing an entire crop genome for the same price as a barrel of oil, the chances of doubling the rate of genetic gain look increasingly probable.

Prices, efficiency and productivity

The decline in real prices of cereals of 1.8-2.6% per annum since 1960 has been a major source of poverty reduction. This has been driven by a 1.7% annual growth in total factor productivity in main producing countries (Fuglie 2008). Prices for non-renewable inputs with no obvious substitutes are likely to rise, especially for phosphates, nitrogen and energy. N use on maize in the USA stabilised around 1980 and N use efficiency (NUE) has increased steadily since then as yields have risen (Fig. 1B) – a trend that applies to other nutrients as well. N use in Asia is now steadying, but in sub-Saharan Africa where rates are 10% of those of Asia, there is an urgent need for increased use of N. Meanwhile, improving N recovery by crops (commonly only 40% or less) and enhancing biological N fixation will directly improve NUE. Conservation tillage, currently practiced on less than 10% of arable land (FAO 2008), is an obvious means of saving energy and conserving soil. Of major concern is the supply of phosphorus, since Cordell *et al.* (2009) predict a decline in production of phosphates by 2034. Other studies (van Kauwenbergh 2010) are less pessimistic, but no-one doubts that prices of P will increase and P recycling from animal/human excreta is likely to become more common. For N, P and water, precision application is becoming increasingly attractive at the farm level. Continued growth in total factor productivity will be driven by extension of new technologies, using the internet and cell phones. Considerably greater investments in R & D will be needed. Rosegrant *et al.* (2008) predict that a 13% increase in R & D expenditure over current levels will lift annual yield gains by 40%. This optimistic forecast is tempered by the exponential increase in R & D expenditure needed to maintain the current linear increase in maize yields (Duvick & Cassman 1999).

Conclusions

We remain cautiously optimistic that the world will be able to feed itself in 2050, based on the existence of large and exploitable yield gaps, especially in sub-Saharan Africa and South Asia, and the steady gains made by plant breeders in FY, PY and PY_W. Molecular breeding, though expensive to develop, is becoming mainstream, and could double genetic gain. Several key technologies, notably conservation tillage and transgenic crops, are still used on only 10% of the world's crop land. There are changes underway in policies, infrastructure and institutions in the developing world that favour rapid growth in farm productivity - e.g. roads, rural finance, advisory services, insurance and information technology.

As always there are provisos. Increasing the rate of gain will require perhaps a 50% increase in investment in R & D, and increased efficiencies through sharing technologies within megaenvironments and between private and public institutions. Attracting large private sector investments in rice and wheat will depend on the economic viability of hybrids in those crops or other techniques that guarantee rewards to investors. Private-public partnerships will be essential, and the recent revamping of the CGIAR is a key step to conserving, identifying and exploiting new genetic variability. Hard choices between alternative energy sources and food security may have to be made, since 28% of the

US maize crop is currently used for ethanol. Non-renewable inputs, especially fossil water, energy, N and P, will inexorably increase in price, and may show alarming spikes whenever supplies are interrupted. Population growth is slowing globally but continues to be rapid in some key regions where food security is already tenuous. Climate change will reduce yields in the tropics if the rate of turnover of new adapted varieties is too slow, or if genetic variation and/or investment are insufficient. Societal acceptance of GM food staples, such as rice and wheat will eventually occur among the more needy nations, but if this is delayed it will rob breeders of important tools and slow needed productivity progress.

The technology pipeline takes a number of years to fill: the time to start is now, and there has never been a more important time to focus on high quality, field-based agricultural research. Darwin, whose bicentennial birthday was celebrated in 2009, remarked: "If the misery of the poor be caused not by the laws of nature but by our institutions, great is our sin". This wise admonition still applies today.

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