6.7 New tools, efficiency and structures for yield breeding

Conventional plant breeding is a relatively slow, somewhat empirical but very successful process resulting in genetic gains in raised PY and PY_W that have matched demand for grains over the past century. It has depended on large investments in empirical yield testing, and been driven by genetic diversity supplemented by effective wide crossing. Progress has been aided by developments in genetics, population theory, crop and genetic modelling, plot mechanization, robotics, remote sensing, biometry, computing and environmental characterization. Despite this, yield progress through breeding as a percent of current yield, and in an absolute sense, has been declining over the past decades for rice and wheat (Section 4), but apparently not for maize, although gain per unit of investment has probably been declining for some time in maize also (Duvick and Cassman, 1999).

Molecular breeding technologies offer real hope of accelerated progress, provided useful genetic variation continues to be available. These technologies, most notably marker-assisted selection (MAS), marker-assisted recurrent selection (MARS) and transgenics, are now being integrated with conventional breeding approaches, but have not been widely adopted outside of industry leaders in the private sector because of capital constraints. As noted previously, Monsanto, a leading global seed company, has set a goal of doubling maize yields between 2000 and 2030 (www.monsanto.mediaroom.com), calling for gains in yield 2.5 times the historical rate from 1960-2008.

Are such yield gains probable, or even possible? Leading private seed companies are investing considerable resources in maize breeding, blending conventional breeding with MAS, MARS and transgenics, coupled with extensive multilocation testing. Early MARS studies using association mapping suggest that gains in yield in elite germplasm of four percent per year are possible (Crosbie *et al.*, 2006) in favourable and stressed environments, effectively doubling the rate of yield gain compared to conventional breeding (Eathington *et al.*. 2007; Edgerton, 2009). Association mapping is based on dense marker maps, usually using single nucleotide polymorphisms (SNPs) a full-genome marker scan, accurate yield assessment, and statistical algorithms that develop many gene- to-phenotype associations (Heffner *et al.*, 2009). However, the big question is how useful transgenic variation will be in bringing in novel variation to supplement the natural variation for grain yield traits, like RUE, functional stay-green that tolerates drought, for root growth that explores the soil volume more thoroughly, and for some types of drought tolerance. If maize was engineered to tolerate light frosts, this would extend its effective season length in temperate environments, and increase its yield potential; the same would apply to rainfed wheat intermediate latitudes, where frost resistance at flowering would likely bring earlier flowering and significant yield benefits in addition to the conventional and molecular marker assisted gains. These additional GM gains appear technically feasible, but much less certain.

Realizing these additional gains requires that the genetic variation (natural or transgenic) is present and that genotypic (i.e. laboratory assays of genes and markers) and phenotypic data (i.e. field measures of plant performance) can be brought together in the tight time frame demanded by large breeding programs today; physiological understanding will be critical to yield increase via GM, but is less so for MAS and MARS. The latter will depend more on whether methods for detection of gene-phenotype associations and their use within a routine pedigree breeding system, such as “mapping as you go” (Podlich e*t al.*, 2004), deliver on their early promise. Phenotyping capability in the field and greenhouse is expanding much more slowly than our ability to genotype huge arrays of germplasm in the laboratory, and cost per phenotypic data point is declining much more slowly that cost per genotypic datapoint, - yet both classes of data are critical to future success in crop improvement. Improvements in phenotyping efficiency will depend strongly on a combination of carefully managed stress levels in the field and remote sensing of large numbers of plants, again with a bigger role from physiology than in the past. Finally, such changes will likely require significant advances in agronomy, especially in N nutrition, if they are to be exploited fully in the farmer’s field.

Intellectual property (IP) considerations are a constraint to widespread use of molecular breeding techniques, yet it is these that offer the protection that ensures continued private sector investment. IP protection, coupled with use of hybrids, where farmers and companies benefit from annual purchase of seeds, provide a powerful incentive for investment in crop improvement, and are reflected partly in the greater genetic gain seen in maize than in rice and wheat. There are advantages of scale in global breeding, seen initially in the international breeding programs of CGIAR centres like CIMMYT and IRRI and currently in the global operations of multinationals like Monsanto, Dupont, Syngenta and Bayer. Research alliances between SMEs, CGIAR centres and the multinational seed companies addressing needs of national or niche markets have generated viable business models for seed SMEs, needed to maintain a healthy competitive environment in the seed industry.

Transformation and marker-aided backcrossing is now relatively cheap and routine. However the search for appropriate candidate transgenes, IP agreements and royalties, regulatory compliance, and commercialization are expensive undertakings, perhaps costing $50-70 million per gene in industrial countries. The scale of these costs excludes many developing countries and SMEs from this technology, and the recent agreements to waive IP restrictions on the use of technologies associated with high pro-Vitamin A "Golden Rice" and the WEMA Project are welcome signs of corporate social responsibility and public-private collaboration. Regulatory compliance costs have increased greatly in recent years. This reflects societal unease with GM technology, but should reduce in time, as experience reveals the true level of risk. At present, with very few exceptions, that unease has prevented commercial use of transgenes in major food staples. It is safe to assume that by 2050 transgenic technology will still be monitored, but will be cheaper, far more widely available, and used to a much greater extent to improve PY and yield stability of staple food crops.

6.8 Concluding comments: Yield potential toward 2050

Prophecy is an uncertain business, and can only be based on extrapolation of existing trends. Needed is an accelerated gain in cereal yields on the farm from less than one percent to around one percent annually: this will largely come from new varieties with increased PY helped by the development of agronomic practices that exploit this new capability while conserving agriculture's natural resource base; in addition new varieties will need to be able to cope with climate change. Areas calling for **increased research investment** are:

- Conventional breeding increasingly aided by genome analysis and other molecular marker-aided breeding focused on increasing PY and PY_W, and possibly underlying key mechanisms. This will involve sequencing genomes of a diverse but representative array of rice, wheat and maize genotypes, and must be linked with high throughput precise protected phenotyping facilities, as well as representative production fields with managed input levels (e.g. water supply). Physiology, informatics and biometrics are critical tools here.
- Increased photosynthetic rates, using conventional but targeted approaches, as well as longer term transgenic ones such as developing C_4 options for rice and wheat, or otherwise increasing the efficiency of net photosynthesis in warmer environments by modifying Rubisco, Rubisco activase and the enzymes that modulate photorespiration in C_3 plants. Since crop plants have finely balanced source: sink interrelationships (Denison, 2007), a major change in source will take several decades of adaptive breeding to deliver its full benefits as grain yield.
- Eliminating outcrossing barriers for successful hybrid production in rice and wheat.
- Crop genetic enhancement through the use of wild species (see Ortiz *et al.* 2008, for wheat).
- Continued focus on stress tolerance as well as PY in all crops will continue the trend towards higher yields, enhanced yield stability, and improved input use efficiency evident in the temperate maize crop today.
- Continued strong investment on protecting genetic and agronomic gains through pest resistance, since climate change will bring changes in the balance of pest and predator. The global soil resource must also be protected from erosion, a huge unfulfilled role for conservation tillage, and from degradation caused by nutrient depletion, an unescapable role for efficient use of chemical fertilizers.

A suitable **policy framework** is needed to attract private investment and to develop technology and guide its benefits to those most in need.

- A strong but balanced emphasis on IP protection for molecular and varietal products and on F1 hybrid production in maize, wheat and rice.
- Societal acceptance of transgenic food products, and reduced costs of transgene deregulation will greatly increase the range of tools at the breeder's disposal.
- Development of a win-win social contract that sees technology outcomes shared with resource-poor countries and sees more private-public partnerships in the developing world. We regard both private and public sectors as key components of efficient international agricultural research, and see a strengthening of the CGIAR system and of regional and global commercial activities as essential complements.

7. PRICES, EFFICIENCY AND PRODUCTIVITY

Our ultimate concern is not with yields *per se*, but with improving productivity and reducing prices of food staples. Declining real prices of food staples for 1961-2006 at an annual average rate of 1.8 percent for wheat, 2.6 percent for rice and 2.2 percent for maize in world markets has been a major source of poverty reduction, given that food staples make up a large share of expenditures of the world's poor.[14] This decline in real prices has been driven by growth in total factor productivity, averaging 1.0 percent globally for all agriculture for the period, 1961-2006, but 1.7 percent for the industrial countries who provide most grain exports (Fuglie, 2008). A distinguishing feature of this period has been that TFP has risen faster than prices have declined, so that both farmers and consumers have benefited (Lipton, 2005).

This final section reviews the prospects for sustainable productivity growth and food prices. In particular, we briefly analyze three major determinants of future prices; (i) pressure from rising prices of non-renewable resources and the need for more sustainable systems, (ii) opportunities to close efficiency gaps, and (iii) prospects for continuing gains in TFP.

7.1 Prices of non-renewables

Looking out to 2050, the potential for sharply increasing prices of non-renewable resources that have no close substitutes could have major implications for crop yields and food prices. The two resources of most concern are fossil fuels for manufacture of nitrogenous fertilizers and provision of farm power, and reserves of phosphates, an essential macro-element for soil fertility.

7.1.1 Fossil fuels

All indications are that fossil fuels have entered a new era of higher and more volatile prices with an expected upward trend. Modern agriculture uses an estimated 12.8 EJ[15] of fossil energy or about 3.6 percent of global fossil fuel consumption. This is roughly divided between 7 EJ for fuel and machinery, 5 EJ for fertilizer, 90 percent of which is for N, and the rest for irrigation and pesticides (Smil, 2008). The intensity of commercial energy consumption (nearly all from fossil fuels) varies widely from about 0.14-0.16 GJ/t grain in rice in the Philippines and maize in Mexico in traditional systems, to 2.4 GJ[16]/t for improved rice in the Philippines, 2.5 GJ/t of wheat in Germany and 5.9 GJ/t for irrigated maize in the US (FAO, 2000; Langreid *et al.*, 2004). Both machinery and fertilizer costs are a growing share of production costs in developing countries (World Bank, 2007).

Nitrogen: Current global consumption of around 100 Mt of N fertilizer provides over two thirds of N supplied to crops (Socolow, 1999). Although N fertilizer use is now falling in industrial countries, it continues to rise in developing countries (Section 3). Future projections of N fertilizer consumption vary widely from a relatively modest increase to 121 Mt in 2050 (Wood et al., 2004) to 180 Mt in 2070 (Frink et al. 1999), depending on assumptions including N use efficiency.

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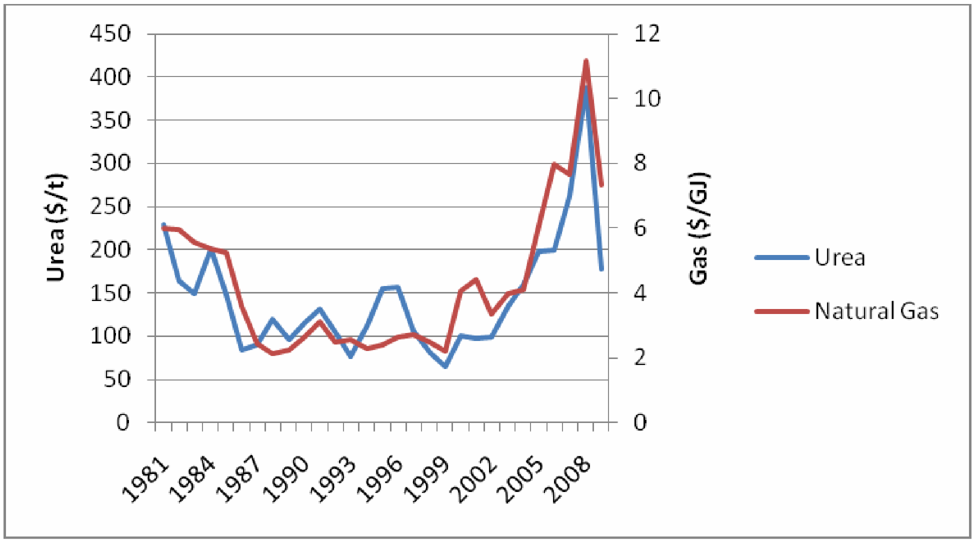
[14] For a review of evidence see World Bank, 2007.
[15] EJ = 10^{18} Joules
[16] GJ = 10^9; 1 litre of diesel contains 38 MJ, 1 ton of maize or wheat about 15 GJ.

Fossil energy (usually natural gas) accounts for 70-80 percent of the cost of manufacturing N fertilizer.[17] Increased efficiency in manufacturing N fertilizer had allowed N fertilizer prices to fall until the 1980s. For example, energy to manufacture ammonia using the best technology at the time has declined from 50-55 GJ/t NH_3 in 1950 to 35-40 GJ/t in 1970 to about 27GJ/t in 2000 (Smil, 2008).[18] However, the best plants are now approaching the stoichiometric limit for energy efficiency. Since 1981, N prices have closely tracked energy prices, a ton of urea (46 percent N) costing about 40 times a GJ of natural gas (Figure 7.1) although significant efficiency gains could still be made by mothballing older less efficient plants.

Figure 7.1: Real price of Urea (bulk E. Europe) and natural gas (Europe) ($US2000)



Source: World Bank data files

Since the major efficiency gains have already been made, it is likely that the price of N fertilizer will rise in tune with energy prices. In addition, some high income countries are now taxing N fertilizer use as a disincentive to pollution. A tax on green house gas emissions is also likely in the future. This would hit prices of N fertilizer particularly hard due to its fossil energy intensity as well as the fact that upon application it can become a significant source of nitrous oxide, an especially potent green house gas that accounts for about one third of all agricultural greenhouse gas emissions (Crutzen *et al.*, 2008).

Increasing the efficiency of on-farm use of N and the supply of biologically fixed nitrogen are the best options for confronting rising N prices. Numerous studies have documented low on-farm efficiency of applied N, with an average of 33 percent being taken up by the crop, and only 29 percent in developing countries (Raun and Johnson, 1999). Many Chinese farmers may be using N at above optimum levels (Buresh *et al.*, 2004). With better management and lower rates being applied in many cases, N-use efficiency could be improved by 33 percent for irrigated maize to over 100 percent for rainfed rice (Balasubramanian *et al.*, 2004) (Table 7.1). Improvement is already evident in maize in the United States of America for example, where N use per ha has declined through more site-specific application rates, even as yields have increased (Section 4). Precision agriculture provides new tools to further improve efficiency (discussed below). New products such as controlled and slow release fertilizer can also increase efficiency rice (IFDC, 2009). In Bangladesh, over half a million

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[17] The actual figure varies based on location and age of the manufacturing plant, the fertilizer product and natural gas costs. Although natural gas is cheap in the Gulf states, fertilizer must still be transported to the point of consumption (A. Roy, pers. comm.).

[18] The conversion of ammonia to urea adds 10 GJ/t N to the energy costs of fertilizer, giving a final energy cost of urea of 55-58 GJ/tN (Smil, 2008).

farmers have adopted Urea Super Granules that are deeply placed at planting time enabling N use to be cut by about one third with a corresponding increase in yields of almost 20 percent (IFDC, 2007). Finally, as plant breeding has raised yield, inevitably it has resulted in more efficient N use (Ortiz-Monasterio *et al.*, 1997; Bänziger *et al.*, 1999; Echarte *et al.*, 2008); this is a general principle which applies to most other inputs (e.g phosphorus, water) as well (de Wit, 1992; Fischer, 2009).

Biological N fixation is the other major opportunity for increasing the supply of N, while reducing the dependence on fossil fuels. Biological fixation already accounts for about one third of world N supply to agriculture, and more in some countries such as Australia. Although legumes only cover about 11 percent of cropped land, there are still important opportunities to fit legumes into even relatively intensive systems, as shown by the adoption of 60-day mung beans on nearly 1 M ha in the rice-wheat system of the Indo-Gangetic plains that has reduced the cost of the following wheat crop by 23 percent (Ali *et al.*, 1997). N-fixation in cereals themselves is also being researched but it is unlikely that this would be a feasible technology by 2050 and the gain in N would have to be balanced against a probable yield penalty for energy diverted to N fixation (Ladha and Reddy, 2000).

Table 7.1. Mean Recovery Efficiency of N (RE_N, percent of N fertilizer applied) for harvest crops under current farming practices and research plots

Crops	Mean RE_N under current farming practice (%)	Mean RE_N in research plots (%)	Maximum RE_N of research plots (%)
Rice			
• Irrigated	31-36 (Asia)	46-49	88
• Rainfed	20	45	55
Wheat			
• Irrigated	33-34 (India)	45-57	96
• Rainfed	17 (United States of America)	25	65
Maize			
• Irrigated & rainfed	36-57	42-65	88

Source: Balasubramanian *et al.*, 2004 ; Dobermann, 2007

Farm power: Conservation farming using zero tillage is a major opportunity to reduce fuel use for farm power in agriculture by an average of 66-75 percent, as well as sequester soil carbon. No-tillage is now used on an estimated 100 M ha globally out of about 1170 M ha of cropped land (FAO, 2008), with a large concentration in the Americas where wide adoption of transgenic herbicide resistant maize and soybeans has strongly accelerated the trend (Brookes and Barfoot, 2008) (Table 7.2). However, there are also good examples from irrigated South Asian systems of wide adoption by small-scale farmers of zero tillage on as much as 5 M ha of wheat in rice-wheat systems, with an estimated savings in fuel costs of 60-90 percent and an increase in wheat yields of 11 percent (Erenstein *et al.*, 2008; Derpsch and Friedrich, 2008).[19] Conservation tillage is also a potentially important source of carbon sequestration in tropical soils (IPCC, 2007).

With less than 10 percent of the world's crop land under conservation tillage, wider adoption of the practice represents a major opportunity to improve the sustainability, energy efficiency and yield of cropping. But conservation agriculture is knowledge intensive and location specific and will require sharply increased investment in research on suitable varieties, management practices adapted to specific sites, appropriate machinery, and advisory services and farmer networks. Current discussion of payments for soil C sequestration

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[19] This figure is not included in Table 7.2 since farmers practice tillage in the following rice crop, and so it does not meet the strict definition of zero tillage.

leading up to the Copenhagen summit on climate change, will, if successful, greatly add to the incentive to adopt conservation tillage.

Table 7.2: Estimated area under no-tillage in major adopting countries (M ha)

	1988-91	2003-07	Percent coverage, 2003-07
Argentina	0.5	19.7	67
Brazil	1.4	25.5	38
Paraguay		2.1	49
Canada	2.0	13.5	26
United States of America	6.8	25.3	14
Kazakhstan		1.8	8
Australia	0.4	9.0	18
Total[b]	11.4	99.9	≈ 9

[a] No-tillage is defined as a system of planting crops into untilled soil by opening a narrow slot, trench or band only of sufficient width and depth to obtain proper seed coverage. No other soil tillage is done. (Derpsch and Friedrich, 2008).
[b] Total including countries with under 1 M ha in 2003-07.

Source: FAO, 2008

7.1.2 Phosphorus

Phosphorus is the other major non-renewable resource where scarcity could significantly affect crop yields by 2050.[20] Recent work by Cordell *et al.* (2009) estimates peak production of phosphates by 2034, using the Hubbert curve which predicts declining production of oil and other mineral resources when half of reserves have been exploited (Figure 7.2). Production will also become more concentrated especially in Morocco as the United States of America has only 20-25 years of reserves remaining, and China has a high export tax. The quality of deposits is also declining, raising the cost of extraction of remaining reserves.

However, as with N, there is much room to enhance efficiency of P use. Of the 14.9 Mt P mined for agriculture only 6.1 Mt of P is removed in crop biomass. On-farm efficiency can be improved through application of many of the same site specific management practices as for N, though the big difference here is that N is a mobile element that can be leached, while P remains in the soil, slowly building up (in advanced agriculture more P is applied than removed in biomass) in forms which are less available to most plants; microbial additives and genetic engineering of crop roots may improve the accessibility of these unavailable forms of soil P. It is also likely that increased recovery of P from human and animal excreta for use as fertilizer will become common as the technology for recycling is developed and prices of P rise (Cordell *et al.*, 2009).

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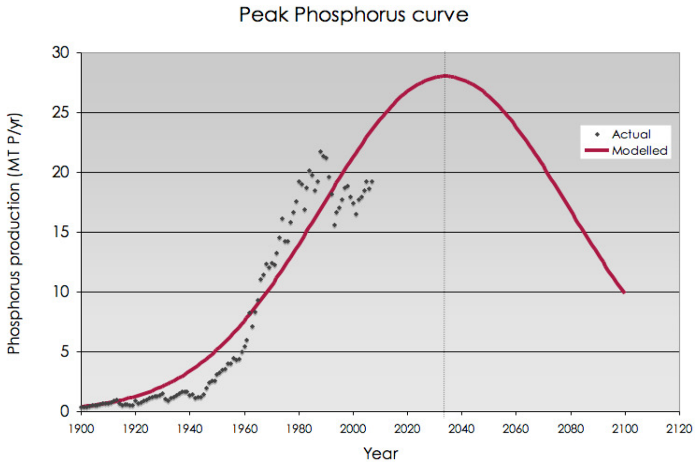
[20] World reserves of potash appear to be sufficient to provide sufficient supplies well beyond 2050, but are concentrated in few locations – 96 percent is produced in North America, Europe and the Middle East (Dobermann, 2007).

Figure 7.2: Projection of Peak Global Phosphorus Extraction



Source: Cordell, Drangert and White (2009)

7.2 The Production efficiency gap

Many areas could produce the same or higher yields with lower input costs through practices designed to enhance input efficiency. Over the past two decades, economists have carried out hundreds of studies to estimate farm level efficiency in relation to the production frontier reached by the best farmers. A meta-analysis of 167 such studies concluded that average technical efficiency is 72 percent with a high of 82 percent for Western Europe and a low of 70 percent for Eastern Europe (Bravo-Ureta *et al.*, 2007).

While most of these studies fail to adequately account for site and season characteristics specific to plots and farms, they find efficiency is most closely related to farmer characteristics, especially education, location, and access to information (Ali and Byerlee, 1991). A further finding is that education has a significant impact on productivity in most post Green Revolution settings where management is increasingly knowledge intensive.

Information and communication technologies (ICT) in what is often termed 'precision agriculture' have much potential to enhance productivity as well as to contribute to more sustainable production systems. These new tools such as yield mapping, leaf testing to time N application, remote sensing, crop modeling and expert systems, improved weather forecasting, and wireless in-field monitoring, aim to improve input use efficiency by allowing inputs to be more precisely calibrated to within-field variability and seasonal conditions (Sudduth, 2007). In small farm agriculture these techniques are also being applied. The leaf color chart is being used by very small farmers to time N application on rice (Islam *et al.*, 2007). And with the spread of mobile phones and village information kiosks, farmers can increasingly tap external sources of information on prices and crop management as well as identify pests and diseases remotely.

However, this type of "precision farming" will require greatly improved knowledge transfer systems, additional equipment, and skilled and educated farmers to achieve its full potential. To date, the potential of this information technology revolution has received too little attention relative to the biotechnology revolution.

7.3 Agricultural price policies

Price policies can also be important to achieving high yields and efficiency. Historically, developing countries have heavily taxed their agricultural sectors in part to provide cheap food, penalizing overall rates of growth of the sector. This situation has largely been resolved under liberalization policies of the 1990s, and the average tax on agriculture is now low (Anderson, 2009). This has provided a one-off opportunity to spur productivity growth which will not be available in the future. However, yields of food crops are generally quite inelastic with respect to prices, at least in the short term (Binswanger, 1989; Rosegrant *et al.*, 2008). Progress in dismantling price distortions has been much slower in industrial countries where farm subsidy programs have favored a few crops and discriminated against adoption of more sustainable cropping systems, especially crop rotations.

Subsidies on many inputs and outmoded pricing structures for inputs, especially water, are still common in Asia. These policies played a role in stimulating adoption of Green Revolution inputs in the 1970s and 1980s, but given current high levels of input use, they undermine incentives to use inputs more efficiently. Supporting institutional reforms will also be important—for example, the greater devolution of water management decisions to users, and a gradual shift to market-determined water allocation systems.

In Africa where yields and input use are still very low, there is a case for 'market smart' input subsidies to promote adoption of fertilizers and stimulate input market development. Several countries have re-introduced such subsidies (World Bank, 2007). However, high fiscal costs and displacement of commercial sales threaten their long-run sustainability and effectiveness.

7.4 Prospects for TFP growth

Finally, what does all of this mean for TFP growth? In general, TFP growth accounts for a higher share of agricultural output growth as agricultural economies develop (Pingali and Heisey, 1999). TFP growth was responsible for half of output growth after 1960 in China and India, and 30–40 percent of the increased output in Indonesia and Thailand (World Bank, 2007). There is little evidence that growth in TFP is slowing (Box 7.1).

TFP growth is largely explained by investments in research, extension, education, irrigation, and roads as well as policy and institutional changes (Pingali and Heisey, 1999; Binswanger, 1989; World Bank, 2007; Kumar, 2008). Decompositions of productivity gains consistently point to investment in research often associated with extension as the most important source of growth. Improved varieties alone contributed as much as half of total factor productivity gains in Pakistan and China in the post Green Revolution period (Rozelle at al., 2003; Ali and Byerlee, 2002). Even in Sub-Saharan Africa, the impact of R&D has been identified as important in its (limited) productivity growth (Lusigi and Thirtle, 1997).

Box 7.1: Is TFP Growth Slowing?

Recent work by Fuglie (2008) provides an up to date and comprehensive overview of TFP growth (Table 7.3). While these estimates are for all agriculture and not just for cereals, the general conclusion is that TFP growth has accelerated in the most recent period since the Green Revolution, 1991-06, in spite of slower output growth. Input growth has slowed in all regions, and in developed countries is now negative. This is especially so in the former Soviet block, where inputs were used very inefficiently before the transition to markets.

In developing countries, total output growth has not slowed, implying that growth from diversification to higher value products has canceled slower growth in cereals. High growth in both output and TFP is led by large countries, especially Brazil and China, with TFP growth above 3 percent/year. Nonetheless, Fuglie (2008) recognizes that cereal growth has slowed significantly and that TFP for individual commodity groups may show different patterns. Indeed, a recent review by Kumar *et al.* (2008) suggests some slowing of TFP growth in cereals in South Asia, with negative growth in rice in the Punjab. This supports earlier evidence of slowing TFP growth in rice-wheat systems in India and Pakistan (Murgai *et al.*, 2001).

Overall, the share of growth accounted for by TFP has risen from one third in the period 1970-90 to nearly two thirds in the period, 1991-2006 in developing countries. In line with the earlier analysis, sub-Saharan Africa is the outlier with growth dependent on land expansion rather than TFP—in fact, land area has expanded more rapidly than output, although there is evidence of recent acceleration of productivity growth in some countries such as Ghana (Fuglie, 2009).

Table 7.3: Growth of total output, inputs and total factor productivity (TFP) in agriculture

	Output		**Input**		**TFP**	
Region	1970-90	1991-06	1970-90	1991-06	1970-90	1991-06
	(%/yr)	(%/yr)	(%/yr)	(%/yr)	(%/yr)	(%/yr)
sub-Saharan Africa	2.03	2.67	1.72	1.81	0.31	0.86
Latin America	2.69	3.03	1.68	0.59	1.02	2.44
Asia	3.36	3.57	1.85	0.95	1.51	2.62
MENA	3.15	2.54	2.02	1.01	1.14	1.53
North America	1.49	1.61	0.00	-0.30	1.49	1.91
Europe	1.10	-0.15	-0.16	-1.66	1.26	1.52
Russia, Ukraine and Central Asia	0.99	-1.57	1.17	-3.95	-0.17	2.38
Developed Countries	1.35	0.87	-0.27	-1.18	1.61	2.05
Transitional countries[a]	0.95	-1.48	0.94	-3.28	0.00	1.79
Developing Countries	3.16	3.41	2.08	1.22	1.08	2.19
World	2.16	2.13	1.37	0.57	0.79	1.56

[a] Countries of the former Soviet Union

Source: Fuglie (pers comm), recalculated from Fuglie (2008)

7.5 The key role of R&D investments

The question is what level of investment in R&D will be needed to realize needed gains in yields and productivity to secure global food security to 2050. von Braun *et al.* (2008) estimate that a doubling of investment in R&D in developing countries would increase the contribution of R&D to overall output growth by 1.1 percentage points (i.e. approximate doubling of current rates), sufficient to assure a continued decline in poverty (and presumably food prices) through 2020. This scenario appears to be quite similar to the high R&D investment scenario of Rosegrant *et al.* (2008) that reverses an upward trend in real prices of grain to 2050 relative to the baseline. However, there is a wide margin of uncertainty in estimates of the quantitative relationship between R&D investments and yield and productivity growth, especially the time lags involved, even though ex-post analyses of research impact have invariably yielded very attractive rates of return.

These scenarios do not consider investment in R&D in industrial countries which will continue to play a major role in global food security as developing countries urbanize and likely increase their dependence on food imports. Spillovers from R&D in industrial countries are also important to developing countries. Combined public and private agricultural R&D investment in industrial countries is double that in developing countries. There are worrying signs of reduced public investment in R&D in industrial countries as well as reallocation to non-productivity issues such as food safety and the environment could reduce resources for long term strategic research of relevance to developing countries, such as efforts to push out the yield frontier (Pardey *et al.*, 2007). Meanwhile, private investment in R&D has increased rapidly in industrial countries. A conservative estimate is that the private sector spends about $1 billion annually on maize research in the United States of America, compared with $181 million in 1990 in 2008 dollars (Byerlee and Lopez, 1994). This huge increase is a likely explanation for the continuing impressive yield gains in maize in the United States of America, and in like environments where these companies and their subsidiaries operate.

Nonetheless, there are worries about the sustainability of recent trends in private R&D spending, which has been increasing exponentially while yields have been increasing linearly (Duvick and Cassman, 1999). The large jump in private spending may have finally driven returns to investment in R&D down from their very high levels of over 50 percent to rates closer to a risk-adjusted cost of capital. If so, the era of rapid growth in private investment in maize and soybean research may be over, although the spread of hybrid rice could result in a similar burst of investment in that crop. Unpublished data from the United States Department of Agriculture indicate a leveling of private spending in the United States of America from 2000. One factor that may trigger a new round of private investment in food crops would be if transgenics become accepted by the public for major food staples such as rice and wheat.

Finally, it is likely that over the long term, productivity-enhancing investments are driven by prices. There is evidence that public investment in rice research and irrigation in Asia was negatively affected by the long-term fall in real rice prices (Hayami and Morooka, 1987; Rosegrant and Pingali, 1994). Private research is likely to be even more responsive to prices and the recent increases in food prices may have already led to a resurgence of R&D spending. Thus over the long term, yields may be much more elastic with respect to prices than they are in the short to medium term.

8. CONCLUSIONS

It is common that when world grain prices spike as in 2008, a small fraternity of world food watchers raises the Malthusian specter of a world running out of food. Originally premised on satiating the demon of an exploding population, the demon has evolved to include the livestock revolution, and most recently biofuels. Yet since the 1960s, the global application of science to food production has maintained a strong track record of staying ahead of these demands. Even so, looking to 2050 new demons on the supply side such as water and land scarcity and climate change raise voices that “this time it is different!” But after reviewing what is happening in the breadbaskets of the world and what is in the technology pipeline, we remain cautiously optimistic about the ability of world to feed itself to 2050, as was L.T. Evans at the end of his long excursion through these same issues (Evans, 1998).

First, despite impressive gains in yields over the past 50 years in most of the world, large and economically exploitable yield gaps remain in many places, especially in the developing world and nowhere more so than in sub-Saharan Africa where food supply is the most precarious.

Second, in the short to medium term, there are many technologies that are in their early stage of adoption that promise a win-win combination of enhancing productivity and sustainably managing natural resources. These include conservation farming approaches based on no tillage and the GM technology revolution—both still only used on less than 10 percent of the world's cropland—as well as the even earlier adoption phase of information and communication technologies (ICT) for more efficient and precise management of modern inputs.

Third, yield gains are not achieved by technology alone, but also require complementary changes in policies and institutions. In much of the developing world, policies are now more favorable for rapid productivity growth, while a range of innovations in risk management, market development, rural finance, organizing farmers, and provision of advisory services, show considerable promise to make markets work better and provide a conducive environment for technology adoption. Indeed, in sub-Saharan Africa these innovations are a necessary condition for wider adoption of critical technologies such as fertilizer.

Fourth, plant breeders continue to make steady gains in potential yield and water-limited potential yield, more slowly than in the past for wheat and rice, but with little slackening in the case of maize; there is no physiological reason why these gains cannot be maintained but progress is becoming more difficult with conventional breeding. Genomics and molecular techniques are now being regularly applied to speed the breeding in the leading multinational seed companies and elsewhere, and their costs are falling rapidly. As well, transgenic (GM) technology has a proven record of over a decade of safe and environmentally sound use and its potential to address critical biotic and abiotic stresses of the developing world, with positive consequences for closing the yield gap, has yet to be tapped. We believe that the next seven to ten years will see its application to major food crops in Asia and Africa and that after its initial adoption, the currently high regulatory costs will begin to fall. We note however that this will require significant additional investment, not least in the areas of phenotyping on a large scale, and that it still takes 10-15 years from the initial investment until resulting technologies begin to have major impact on food supply. Transgenics for greater water-limited potential yield may also appear by then, but trangenics for greater potential yield, arising from significant improvements in photosynthesis, may take longer than even our 2050 horizon.

To be sure these are broad generalizations and there are important differences by crop and region. This review of the big three cereals has shown that maize is the dynamic crop, with no evidence of slowing yields and with huge potential in the developing world. It is also the crop experiencing the most rapid increase in demand, largely for feed and fuel, and the crop attracting the largest R&D research budget. Wheat demand and yield growth appear to be intermediate, the latter perhaps because of disease resistance and industrial quality constraints on breeding, as well as the bigger role of water stress in its production environment. Yield gains in rice are more problematic, but demand growth is also less, although it is a particularly important food staple for the poor of Asia, where rice area is shrinking, and increasingly Africa. And although increases in food production in Asia over the past 50 years have been impressive, no country in sub-Saharan Africa has yet experienced a green revolution in food crops in a sustained manner, despite generally better overall performance of the agricultural sector in the past decade.

Yet our review does raise a number of cautions. First, we have not (yet) reviewed other food crops—sorghum and millet, roots and tubers, pulses and oilseeds. Many of these crops are not globally important, but are critical to local food security, cassava in Africa for example. Others are growing commercial crops for an urbanizing population—potatoes for fast foods, and oilseeds for feed.

Second, the future of biofuels is the new wild card in the world food economy. To no small extent the need to accelerate global cereal yield trends beyond the historic annual rate of 43 kg/ha for 1961-2007 relates to this new demand. By 2020, the industrial world could consume as much grain per capita in their vehicles as the developing world consumes per capita directly for food.

Third, many countries face huge challenges in achieving food security, even from a narrow perspective of food supply. We are less concerned about China and India, since they should continue to be largely self sufficient for food needs (although depending on imports for part of their feed needs), but much depends on investments in R&D (below) and management of natural resources. However, there are many countries that do not have the capacity to import large amounts of grain or it would be prohibitively costly to do so, but where population growth is still very high. Most of these are in Africa, but even Pakistan with an estimated 335 m people in 2050 faces a potential food crisis. Climate change will also be a major challenge for many of these countries, adversely affecting yields and diverting R&D resources toward adaptation rather than yield improvement - adding a new dimension to maintenance research.

Finally, past agricultural success has in a sense been achieved by mining of non-renewable resources - fossil energy, phosphate, and much underground water. Our review of the impact of looming limitations of this strategy raises major concerns. This places a premium on improved efficiency of using these resources that must be at the center of the agenda for Feeding the World in 2050. Generally it should be noted that increased yield through breeding and agronomy is lifting resource use efficiency.

The history of agriculture in the twentieth century teaches us that investment in R&D will be the most important determinant of whether our cautious optimism will be realized. We see indications that major developing countries such as China, India and Brazil are poised to close the gap in research intensity with the industrial countries. The CGIAR is also revamping its efforts, aiming to double its budget in the coming years. However, there are many technological orphans that are falling behind in R&D spending (Beintema and Howard, this conference). The private sector too, must be encouraged to make a big impact beyond its mainstays of maize and soybeans, especially in rice. But innovative partnerships will be needed to access and adapt technologies to the world's 800 million small farmers.

Resilience, flexibility and policies that favor R&D investment in staple food research and efficient input use will be the pillars upon which future food security depends. Darwin, whose 200th birthday we celebrated this year leaves two relevant statements: "If the misery of the poor be caused not by the laws of nature, but by our institutions, great is our sin," and, "It is not the strongest of the species that survives….[but]…. the one that is the most adaptable to change."

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