CHAPTER 10

CAN TECHNOLOGY DELIVER ON THE YIELD CHALLENGE TO 2050?

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Projecting crop yields, especially 40 years ahead, is fraught with uncertainty. However, three stylized facts emerge from several recent studies of world food needs. First, given land and water scarcity, climate change and rising energy prices on the supply side, and growing markets for food, feed and fuel on the demand side, global grain markets will be tighter in the future than over the past 40 years. Second, area expansion will at best be small, so future agricultural growth will be more reliant than ever on raising crop and animal yields. Third, the growth rate of cereal yields has been falling since the green revolution years. A major question for this chapter is whether this decline means that crop yields have reached a technological plateau, or there are still large unexploited sources of yield gains either on the shelf or in the research pipeline.

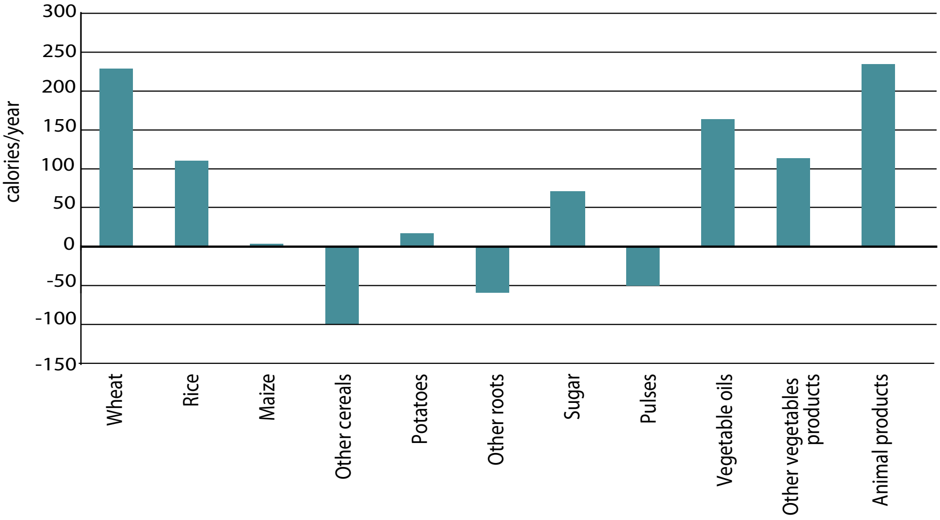
This chapter addresses these questions through the analysis of cereal yields and productivity. It does so by tracing recent sources of growth and identifying future technological opportunities for raising potential yields and closing the gaps between existing yields and those that could be economically attainable by farmers. It focuses on the big three cereals: rice, wheat and maize. Cereals account for 58 percent of annual crop area and provide about 50 percent of food calories. Rice and wheat alone have accounted for about half of the increased per capita energy intake in developing countries since 1960 (Figure 10.1). Maize has been the major source of energy supporting the rapid increase in consumption of animal products (Figure 10.2), accounting for more than 60 percent of energy in commercial animal feeds, and becoming a major feedstock for biofuels in recent years. Together, these three cereals will provide about 80 percent of the increase in cereal consumption to 2050 (Rosegrant *et al.*, 2008). However, the chapter also recognizes that diversification of food production is needed, and a comprehensive review would include relevant data for roots and tubers, pulses and oilseeds. Some of these crops show declining trends, but remain critical to the food security of millions, while others – such as potatoes, sugar cane, soybeans, canola and oil-palm – are booming commercial crops serving multiple uses for food, feed and fuel.

The chapter uses a bottom-up approach that reviews farm survey and experimental evidence on yields and yield gaps in the world's breadbaskets. This allows the discussion to go beyond the estimation of yield growth by simple extrapolation of aggregate trends, to explore the most likely sources of increased yields, including proximate factors, such as higher-yielding varieties, input use and reduced losses from biotic and abiotic stresses, and broader policy and institutional factors that influence crop management and include input market efficiency, risk management, and the information and skills of farmers. The chapter suggests some of the critical investments and institutional changes that will be needed to realize these changes.

Ultimately the chapter is about the potential for sustainable productivity growth, as the effects of productivity on food prices have major welfare implications for poor people. This leads from a discussion of yields *per se* to an assessment of input use and efficiency, and an analysis of trends in total factor productivity. In addition, sustainability is essential, to ensure that productivity can be maintained in the face of depleting non-renewable resources and that production systems do not degrade the environment.

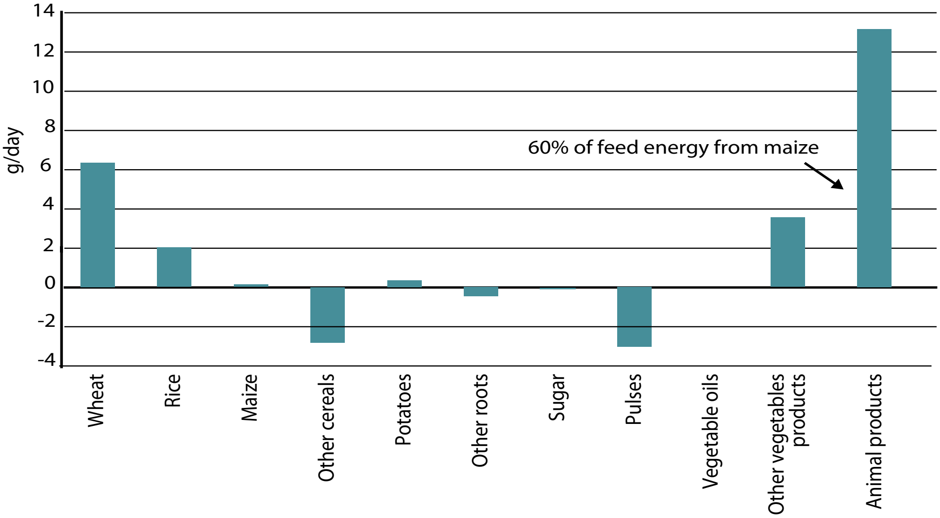
The chapter employs both a global and a local approach to assessing crop yields. Changes in global yields are important for global food security. In a globalizing world, many countries will increasingly depend on trade for provisioning their food needs, and this should encourage production in the lowest-cost regions, if there are no significant trade barriers. However, there are many situations where trade will be inadequate to ensure food supplies. The "megacountries", China and India, have little choice but to produce most of their staple foods, especially rice, given the relatively small, thin world markets in relation to their huge domestic markets. In Africa too, poor infrastructure, land-locked locations and lack of foreign exchange necessitate the production of much of the food near where it is to be consumed. The high population growth in some of the more densely populated African countries adds urgency to accelerating domestic production (e.g., Ethiopia's projected population of 185 million in 2050). The 2008 food price spike, induced partly by export bans and by rising energy costs for long-distance transport, is likely to lead many other countries to put a premium on local supplies.

Figure 10.1
Sources of increased per capita calorie consumption in developing countries, 1961 to 2003



Source: FAOSTAT.

Figure 10.2
Sources of increased per capita protein consumption, developing countries, 1961 to 2003



Source: FAOSTAT.

Defining key concepts

There is a rich and evolving literature on various measures used for yields and efficiency gaps, but these terms are often used very loosely. This section defines the measures used in this chapter and their interpretation, relying largely on the work of Ali and Byerlee (1991), Loomis and Connor (1992) and Evans and Fischer (1999).

There are a number of measures used for crop yield, which here means the weight of grain harvested per unit of field area at a standard moisture content (Table 10.1). The starting point is average farm yield (FY), which forms the basis for calculating the gaps to attainable yield (AY) and then potential yield (PY). Water-limited potential yield (PY_W) is included as a sensible yardstick where crops receive on average only low to moderate water supplies (say < 75 percent of potential evapotranspiration). For increasing FY, which is the objective of this chapter, both increasing PY (or PY_W) and closing the yield gap are important, and somewhat different interventions operate on each. The overall gap PY to FY is considered in some detail because it is often easier to measure, but the key gap is the economically recoverable yield gap under current economics, and it is less, being AYa – FY (Figure 10.3; Table 10.1). Another gap, AYb – AYa, is the gap between attainable yield under efficient institutions and markets (AYb, which is ultimately linked to world prices), and that under current economics (AYa): because current economics are often less favourable to farmers, this gap is often positive, but can be negative where prices are subsidized to help farmers. Throughout this chapter, yield gaps are expressed as percentages of FY, for better comparability with the basis on which demand growth is estimated.

Progress in PY (or PY_W) through genetic and agronomic research is an important source of yield growth because raising the yield frontier lifts other yields as well – a rising tide that lifts all boats. This chapter's section on Sources of yield gains in the breadbaskets presents considerable evidence that $\Delta FY/FY \approx \Delta PY/PY$. However, much also depends on the interactions between genotype and management (Fischer, 2009). Generally, PY progress has exploited positive interactions between the genetic and agronomic routes for improvement in yield. For example, the increase in yields of semi-dwarf wheat and rice varieties at higher levels of management is significantly more than that of the tall varieties they replaced. In advanced systems however, yield increases from agronomy alone, and from these positive interactions, appear to be slowing, although the ongoing synergy between increased maize PY and higher plant population is an exception (Evans and Fischer, 1999).

Table 10.1
Definitions of yield measures

Yield	*Symbol*	*Definition*	*Estimation*
Average farm or on-farm yield	FY	Average yield achieved by farmers in a defined region over several seasons	Regional or national statistics, ground or satellite surveys of fields
Economically attainable yield given current markets and institutions	AYa	Optimum (profit-maximizing) yield given prices paid/received by farmers, taking account of risk and existing institutions	On-farm experiments, varying inputs, sometimes crop models, disaggregated farm surveys
Economically attainable yield assuming efficient markets/institutions	AYb	Optimum yield given prices that would prevail in efficient markets with well-functioning risk insurance markets	As for AYa, but adjusting to the price and risks of efficient markets, etc.
Potential yield	PY	Maximum yield with latest varieties, removing all constraints including moisture, at generally prevailing solar radiation, temperature and day length	Highly controlled on-station experiments or crop models calibrated with latest varieties, well-monitored crop contests
Water-limited potential yield	PY_W	Maximum yield under normal rainfed conditions, removing all constraints except for moisture	Highly controlled on-station experiments, crop models or crop contests
Theoretical yield		Maximum theoretical yield for prevailing solar radiation based on prevailing knowledge of crop physiology and photosynthetic efficiency	Accepted estimate given by the initial slope of the photosynthesis versus solar radiation response curve, discounted for dark respiration

Both farmer characteristics and system-wide constraints explain these various yield gaps and suggest how they may be closed. In general, yield gaps at the lower end, such as AYa – FY, are explained mainly by farmers' access to information and technical skills, while higher-order yield gaps reflect opportunities for research and broader policy and institutional constraints. Figure 10.3 depicts these overlapping sources of yield gaps.

These various definitions assume that underlying site characteristics, soil, climate and seasonal conditions that are beyond the control of farmers are uniform across a defined area. In reality, regional surveys reveal large variation in yields across farmers and fields, around the average FY, in part caused by site and season differences.[1] Often the distribution is negatively skewed (e.g., Lobell *et al.*, 2003),

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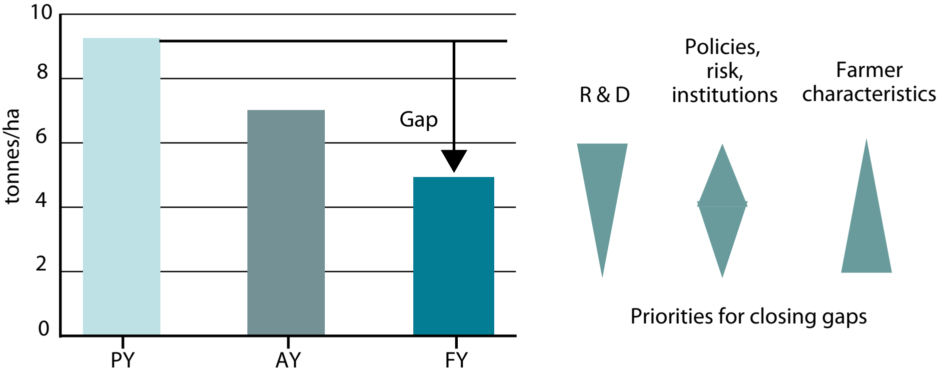
[1] This can be called the non-manageable natural resource base of the site. However, it depends on the time scale. Drainage, liming and terracing can be considered long-term investments to improve an initially deficient natural resource base.

but it is not clear how to relate such distributions to the prevailing AYa and PY. It might be expected that a proportion of farmers will always reach AYa, and a few reach PY. Crop contests that measure crop yield properly on sufficient field size (say > 4 ha) usually give very high yields, which can sometimes be taken as the prevailing PY when better sources are lacking. However, it is important to know whether the natural resource base of the winning fields (the part that cannot be changed with good management) is representative of the region. Similarly, experimental stations may be in more favourable sites, and the PY they estimate can be inflated by these site characteristics. In addition, optimum management is partly a function of seasonal conditions that are not known at the time of decision-making, so part of any yield gap is unpredictable and arises from the interaction between management (including variety choice) and variable seasonal conditions; risk aversion exaggerates this gap in rainfed situations.

As with site differences, the prices and institutions faced by farmers can vary, even within small areas. These differences may relate to farm size, to education, aspiration and skill differences, to differential access to credit and input markets, and to local power structures. Thus part of the gap between good and average FYs may be due in part to site characteristics (some of which might vary at random across years), and in part to differences among farmers in characteristics, resource constraints and prices.

Figure 10.3
Schematic view of key yields and yield gaps for a hypothetical favourable cereal region, and ways of closing them



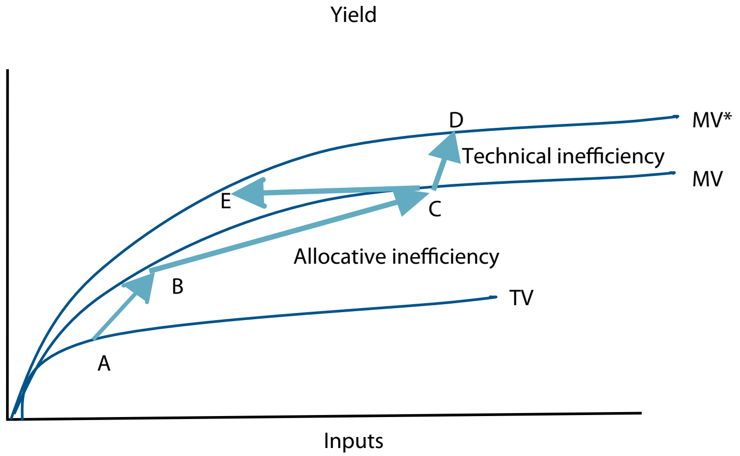
Source: Authors.

For reasons of both productivity and sustainability, this chapter is also interested in efficiency and the prospects of closing efficiency gaps. Put simply, efficiency is measured as the average cost for producing a given yield, relative to the lowest-cost option.

Economists generally distinguish between technical and allocative efficiency. Technical inefficiency refers to a failure to operate on the yield frontier: i.e., the same yield could be produced by using proportionally less of all inputs. Allocative inefficiency refers to failure to meet the marginal conditions for profit maximization where the marginal value of applying an additional unit of input is equal to the price of the input.

In green revolution settings – from Iowa to the Punjab – a useful framework for identifying these inefficiencies with considerable empirical support is given in Figure 10.4.[2] During the green revolution, farmers adopted modern varieties that shifted their production function from traditional varieties (TV) to modern varieties (MV). At the same time, they adopted modest levels of fertilizer and other inputs to reach point B. Initially, however, owing to risk, lack of knowledge and skills, and resource constraints, farmers did not fully exploit the technology and used inputs at sub-optimum levels.

Figure 10.4
Measures of efficiency gaps



Source: Byerlee, 1992.

The first post-green revolution phase was characterized largely by input intensification, moving from B to a point C that is closer to the allocative optimum.

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[2] For simplicity, these efficiency measures are shown in one dimension with one input. Technically, their strict definition requires at least three-dimensional space with two or more inputs.

However, farmers still tended to operate considerably below the production frontier, implying a measure of technical inefficiency. In the second post-green revolution period, the emphasis has been on improving technical efficiency, substituting improved information and managerial skills for higher input use, and moving towards a point D, or – with appropriate incentives or regulations (e.g., on input pollution) – a point E, by reducing input use without sacrificing yields. The yield frontier MV* may be defined in terms of the highest production achieved from a given level of inputs in a population of farmers, or by reference to a potential frontier based on experimental data. In both cases, similar issues of site specificity and seasonal conditions that influence the measurement of yield gaps also affect the efficiency estimate. Most studies by economists have ignored these site and seasonal conditions, and therefore tend to overestimate inefficiency (Ali and Byerlee, 1991; Sherlund, Barrett and Akinwumi, 2002). Of course, MV* is not static but shifts upwards with the release of new technologies, especially newer generations of varieties. It may also shift downwards if there are serious long-term problems of resource degradation.

Yield gaps and efficiency gaps often measure the same things. However, efficiency gaps may exist even where there are no yield gaps. Farmers may be achieving the economically attainable yield, AYa, but using above-optimum input levels. Variation in efficiency across farmers and fields is also explained by factors related to farmer characteristics and system-wide constraints. Technical efficiency relates largely to timing and technical skills in using inputs, and is often explained by farmer-specific knowledge and skills. However, system-level factors such as management of irrigation systems can also explain technical inefficiency. Allocative inefficiency can be due to similar factors, as well as differential risks of using inputs, input market failures and financial constraints.

Ultimately, this chapter focuses on gains in total factor productivity (TFP) as a major determinant of long-term price trends – most productivity increases are ultimately passed on to consumers through lower prices. TFP is a measure of output in relation to the aggregate of all inputs, whereby changes in agricultural production are decomposed into a component relating to changes in inputs and the change due to productivity growth. The primary driver of productivity growth is investment in research and development (R&D) that raises PY. However, research and other factors contribute to TFP growth, such as extension and education that help farmers close yield gap AYa – FY; institutional change or better infrastructure and policy that close yield gap AYb – AYa; or related interventions that narrow efficiency gaps by reducing input costs. Thus TFP is a composite measure of gains in closing gaps, and is referred to later, in the subsection on Prospects for TFP growth.

Setting the scene: recent trends and the challenge to 2050

Much of the concern about feeding the world in 2050 relates to the slowing of yield growth in the major cereals over the past three decades (World Bank, 2007). This section briefly reviews global trends in key inputs and cereal yields, and summarizes available evidence on the growth in yields required to meet the world's food, feed and fuel needs in 2050. Yield trends and causes are disaggregated in the following section.

Recent changes in crop area, key inputs and yields

Land and water inputs are examined fully in other chapters, but being critical to this chapter's analysis they are mentioned briefly here. In recent decades, area growth has been a significant source of production growth in only Latin America and sub-Saharan Africa. Wheat area has fallen in industrial countries, while rice area has increased by only about 0.3 percent annually since 1990, and is actually falling in China, the Republic of Korea and Japan. However, maize area has expanded consistently at more than 1 percent per year in both developing countries (driven by livestock feed) and industrial countries (driven by biofuel demand, mainly in the United States of America). Even so, yield growth has also been the dominant source of production increases in maize (Figure 10.5).

Other crops have also been dynamic. Potatoes – traditionally a staple food in much of Europe – are now grown more extensively in developing countries. Because of both area and yield growth, China is the world's largest potato producer. Soybean has been the fastest growing crop, especially in Latin America, driven by demand for feed (Figure 10.5).

The growth of irrigated area slowed sharply in the 1980s and early 1990s (Rosegrant and Pingali, 1994). However, over the past decade irrigated area has expanded steadily at 0.6 percent per annum in developing countries. Given a productivity differential between irrigated and rainfed areas of 130 percent (Fuglie, 2008), irrigation alone accounted for about 0.2 percentage points in the overall annual yield growth of 1.1 percent for cereal yields from 1991 to 2007.

Increased use of fertilizer has been a major factor explaining perhaps one-third to one-half of yield growth in developing countries since the green revolution (FAO, 2003; Heisey and Norton, 2007). Developing countries now account for 68 percent of total fertilizer use, which has continued to increase by 3.6 percent per year over the past decade, so still accounts for a significant share of yield growth.[3]

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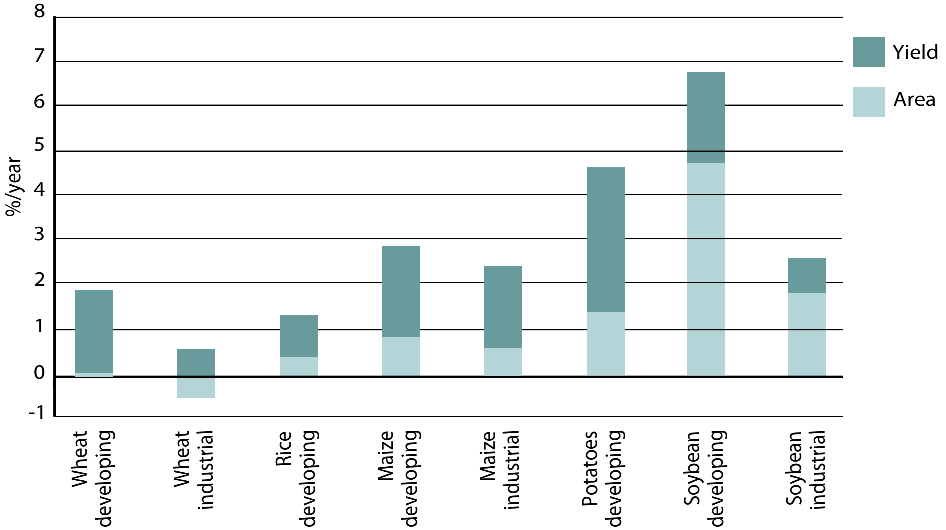
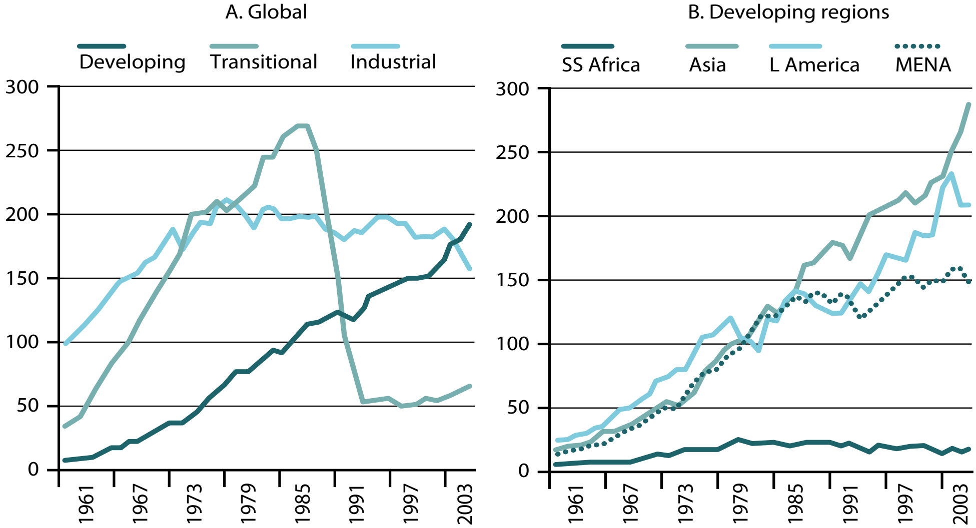
[3] With average rates of fertilizer use on cereals in developing countries of at least 100 kg of nutrients per hectare (Box 10.1), current growth in fertilizer use and a grain-to-nutrient response of 5:1 would add 18 kg/ha additional yield annually, or 0.6 percent.

Figure 10.5
Contributions of area and yield to production growth, 1991 to 2007



Source: FAOSTAT.

Figure 10.6
Trends in fertilizer use (nutrients per irrigated equivalent area)



Sources: Nitrogen, phosphorus pentoxide and potassium oxide ($N + P_2O_5 + K_2O$) from FAOSTAT. Computation of irrigated-equivalent area from Fuglie, 2008.

Using a measure of agricultural area standardized for land quality (Fuglie, 2008), fertilizer use per irrigated-equivalent hectare is also now higher in developing than in industrial countries (Figure 10.6).[4] Globally, fertilizer use has plateaued, owing to a decline in fertilizer use in industrial countries and a dramatic fall in the countries of the former Soviet Union after they moved towards a market economy.

The increase in fertilizer use has been surprisingly consistent across most developing regions. Asia still has the highest and fastest increase, but fertilizer use intensity in Latin America and the Near East and North Africa is comparable. However, fertilizer use per hectare in sub-Saharan Africa is abysmally low, for reasons such as high prices and poor markets, which have been well documented (Morris *et al.*, 2007). Low fertilizer use explains a large part of the lagging productivity growth in that region.

Box 10.1 - Fertilizer use on cereals

Wheat, rice and maize account for about half of all the fertilizer consumed globally. The following table provides data on fertilizer use for some countries and some years. The very high rates in countries such as China suggest little scope for further intensification, and huge scope for improved efficiency. Environmental pressures are likely to lead to pressure to reduce fertilizer use in many countries in Asia.

Estimated fertilizer use for wheat, rice and maize, selected countries

	Total nutrients *(kg/ha)*			Nitrogen *(kg/ha)*		
Country/region	Wheat	Rice	Maize	Wheat	Rice	Maize
Bangladesh		140			100	
China	296	310	213	197	192	180
India	164	160	67	117	106	45
Indonesia		108	146		93	109
Pakistan	182	190	161	140	146	123
Philippines	53	47		46	39	
Iran, Islamic Republic	118			84		
Argentina	77		79	44		46
Brazil	101	95	127	40	29	49
USA	129	250	269	86		152
EU15	186		373	135		227
Poland	142			90		
Sub-Saharan Africa		10	38			
World	128	155	153	87	101	98

Sources: Heffer, 2008; sub-Saharan Africa data from Heisey and Norton, 2007, for the late 1990s.

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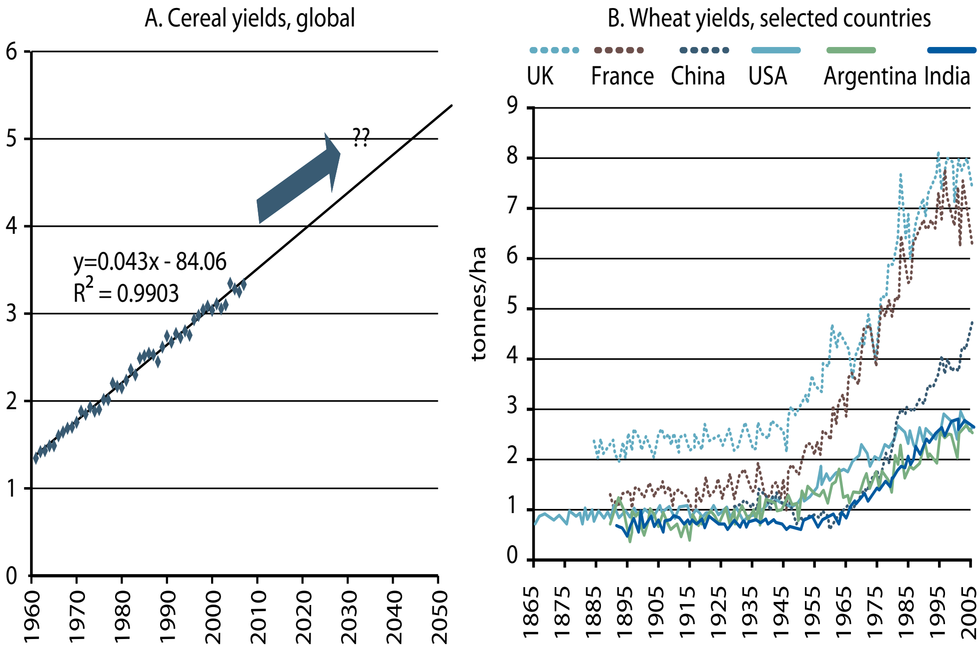
[4] The quality-adjusted agricultural area weights land quality by irrigated, rainfed and pasture, based on relative productivity, to arrive at a rainfed equivalent area (Fuglie, 2008).

Figure 10.7
Long-term trends in cereal and wheat yields



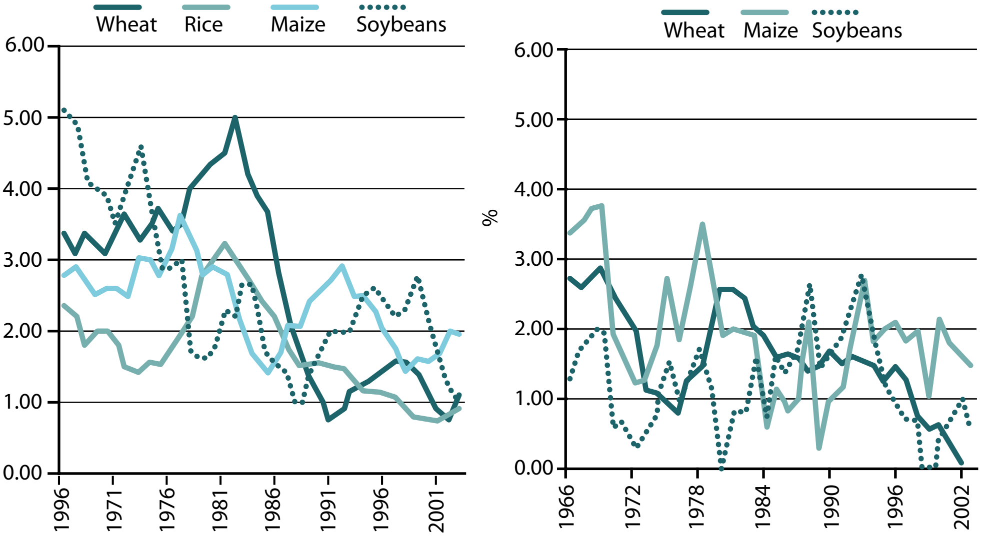
Sources: FAOSTAT; wheat yields updated from Pardey *et al.*, 2007.

Growth through intensification of fertilizer and irrigation use is no longer important in industrial countries. Fertilizer use and irrigation are also already high in some Asian countries, especially China, so their future contribution to yield growth will be modest at best (Box 10.1). However, there are still major regions of the developing world, especially sub-Saharan Africa, where input intensification is at an early stage. In addition, the Russian Federation, Ukraine and other transitional countries are already reversing the collapse of input use, providing scope for more rapid yield growth in the future.

Over the past five decades, global cereal yields have grown linearly at a constant rate of 43 kg per hectare per year, and with very low variability around the trend (Figure 10.7). However, this is a sharp departure from relatively stagnant yields in earlier periods. Note that linear growth in Figure 10.7 implies declining exponential growth, from 3.2 percent per year in 1960 to 1.5 percent in 2000. Projecting the same linear trend to 2050 would deliver annual growth of only 0.8 percent. Global atmospheric carbon dioxide (CO_2) has also increased approximately linearly over recent decades, and it can be estimated from Tubiello *et al.* (2007) that this is contributing about 0.2 percent of current annual yield growth of C_3 crops (such as wheat and rice, but not maize);[5] however C_3 crop yield sensitivity to CO_2 increase is likely to decline as CO_2 increases further.

The aggregate global picture disguises important differences by region and crop, as illustrated for wheat (Figure 10.7). Developing countries experienced a sharp increase in yield growth with the green revolution, and then a sharp drop. The ten-year moving average of growth rates for wheat and rice in developing countries has declined from the mid-1980s to about 1 percent annually in the most recent decade (Figure 10.8). Yield growth of wheat in industrial countries has also slowed, and fell to zero in the most recent decade. The trends for maize, although showing some decline in growth rates in both developed and developing countries, are not nearly so pronounced.

Figure 10.8
Ten-year moving average exponential yield growth rates for wheat, rice, maize and soybean



Growth rates estimated by log linear trend regression. Year refers to the mid-year of the decade.
Source: Computed from FAOSTAT.

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[5] C_3 and C_4 refer to two systems of photosynthesis found in common crop plants, and relate to the number of carbon atoms (three or four) in the primary molecule formed when CO_2 is first absorbed. C_3 species include wheat, rice, soybeans and barley, while common C_4 species are maize, sorghum and sugar cane. The C_4 photosynthetic system has an enzymatic and a morphological adaptation (the so-called "Kranz anatomy") that provides a CO_2-concentrating mechanism in the leaf. This gives it a higher photosynthetic efficiency under high light conditions and a generally greater photosynthetic output under higher temperatures than the C_3 system. Outcomes are usually higher yields and higher water, nitrogen and radiation use efficiencies under warm conditions, compared with C_3 crops.

At the regional level, Latin America has had the best yield performance for all cereals since 1991, averaging 2.5 percent per annum. The lowest average increases have been in sub-Saharan Africa and, surprisingly, East and Southeast Asia, each with about 1.2 to 1.3 percent a year. However, there is some good news in both these regions: sub-Saharan Africa has had a sustained period of modest yield growth from a very low base; and East and Southeast Asia already has high yields of 4.8 tonnes per hectare, so even this modest growth rate represents an achievement.

There is also evidence of a slowdown in absolute yield growth for rice and wheat. The coefficient c of the quadratic term of absolute yield trends was therefore tested by fitting the equation $y = a + bt + ct^2$, where y is national average yield, and t is year. To reduce the impact of the green revolution, the period analysed was 1980 to 2007, after modern varieties were widely adopted. The results indicate a clear slowing of the rate of absolute yield gains in rice and wheat. For wheat, this pattern prevails in most regions, and no region shows an accelerating trend. For rice, the declining trend is very evident in South and Southeast Asia, but Latin America shows an increasing rate of gain.

Again, the results for maize are different, showing a linear trend at the global level and an accelerating trend (positive and significant coefficient c) in the developing world. Both South Asia and Latin America show accelerating trends in absolute gains, while only Western Europe shows a declining trend.

The close linear trend in yield growth at the global level hides considerable heterogeneity in performance by crop and region. Maize has been most dynamic, and Latin America has been the star among regions, partly because maize is the most important grain in that region. As well as exponential growth rates, looking at absolute growth aids the interpretation of trends.

Scenarios to 2050 and the future yield challenge

Against this background, what rate of yield growth is needed to meet the food needs of the projected 9.2 billion people in the world's population in 2050? Studies by Rosegrant *et al.* (2008) at the International Food Policy Research Institute (IFPRI) and Tweeten and Thompson (2008) provide recent analyses of this challenge, while Hubert *et al.* (2010) provide a more accessible version of the IFPRI study.

Global demand and supply prospects are examined in depth in other chapters. Demand for grains is largely determined by population and income growth, with the recent addition of demand for biofuels. At the global level, per capita demand for cereals for food is projected to fall in all regions except sub-Saharan Africa, as increasingly affluent consumers diversify diets to higher-value products, including livestock ones. Livestock in turn will drive demand for feedgrain, especially maize. In addition, maize and some wheat will be used as feedstocks for biofuels. IFPRI projects that this demand for grain for biofuels will continue to increase to 2020/2025 before levelling off as second-generation technologies based on biomass conversion become available (Rosegrant *et al.*, 2008). Still, by 2020 industrial countries will consume about 150 kg per capita of mostly maize for biofuels, which is similar to today's per capita consumption of cereals for food in developing countries.

Tweeten and Thompson (2008) provide a simple analysis of what might happen by 2050 with linear growth in yields of major product groups, including cereals. They project an increase in cereal supply of 71 percent over 2000, or a total increase of 1.4 billion tonnes. This derives from projecting the linear annual yield growth of 43 kg per hectare suggested in Figure 10.7 over the whole period (the initial growth of 1.4 percent becomes 1.07 percent for the whole period).[6] Their middle estimate of demand growth gives an increase of 79 percent by 2050 (1.17 percent exponential over the whole period, with a world population of 9.1 billion in 2050). Thus, there will be a projected supply deficit in relation to demand, which implies an increase in weighted real agricultural prices of 44 percent by 2050 to "clear the market".

Using mid-range (baseline) estimates of population (9.2 billion by 2050), income growth and biofuel demands, Rosegrant *et al.* (2008) project an overall increase in cereal demand of 1.048 billion tonnes (56 percent) by 2050, from a 2000 base. This implies an average annual growth of 0.9 percent over the period, but the authors see demand growth declining from 1.4 percent in the first 25 years to 0.4 percent in the second. Fully 41 percent of this increase is for feed, especially in developing countries. As a result, maize accounts for 45 percent of the increase in cereal demand, wheat for 26 percent, and rice for only 8 percent.

On the supply side, Rosegrant *et al.* (2008) see land and water become increasingly constraining. Area devoted to cereals declines globally by 28 million ha, as loss of cropland and crop diversification in industrial countries and Asia cancels area expansion in Latin America and sub-Saharan Africa. Water available for agriculture also hardly increases, owing to competition from non-farm sectors, declining groundwater tables in the breadbaskets of India and China, and likely higher energy costs for irrigation (Molden, 2007; Tweeten and Thompson, 2008). Some 60 percent of global cereal production is now from irrigated areas, and with competition within these areas for higher-value production, projected irrigated area for cereals falls. Maize is the only cereal expected to show modest area expansion.

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[6] Tweeten and Thompson (2008) assume no change in area, so yield growth is equal to production growth.

The IFPRI projections also take account of climate change. However, climate change in the medium projection of the Intergovernmental Panel on Climate Change (IPCC) is not expected to have a significant effect on global yields by 2050 (IPCC, 2007), as yield gains in some regions (mostly temperate) balance losses in others (mostly tropical). The impacts of climate change are addressed in more depth in other chapters.

The IFPRI yield projections are based on the FAO expert opinions disaggregated by country and agro-ecological zone (FAO, 2003). Overall yield growth in the baseline projection for cereals is 1.0 percent per annum. Averaged for irrigated and rainfed production, the gains are 1.0 percent for wheat, 0.7 percent for rice and 0.9 percent for maize. FAO projections for 2030 are quite similar (FAO, 2003).

The global average annual absolute rate of yield gain to 2050 in the Rosegrant *et al.* (2008) projections (made more accessible by Hubert *et al.*, 2010) is 37 kg per hectare, 14 percent lower than the linear projection of past performance used by Tweeten and Thompson (2008). Given lower yield growth, the IFPRI baseline projects higher real price increases, of 91 percent for wheat, 60 percent for rice and 97 percent for maize from a 2000 base. Developing countries will increasingly depend on imports of cereals (and oilseeds) from industrial countries, Eastern Europe (including the Russian Federation), Brazil and Argentina.

Projections are only estimates, and the overall results are quite sensitive to the assumptions. In particular, Rosegrant *et al.* (2008) show that with an increase in public investment in agriculture of 13 percent over the baseline, especially in R&D, producing a 0.4 percentage point increase in annual yield growth, to 1.43 percent, world grain prices would resume their downwards trend characteristic of much of the past century, and could result in an almost halving of the number of malnourished children by 2050. By contrast, a yield growth of 0.4 percentage points lower (at 0.61 percent) would lead to a more than doubling of real cereal prices, to about USD 600 per tonne (in 2000 dollars) and stagnation in the number of malnourished people.

These studies have two major implications for the analysis of future yield perspectives. First, a continuous linear increase in yields at the global level, following the pattern established over the past few decades, will not be sufficient to meet food, feed and fuel needs – i.e., future demands at or below today's real prices. The world will need to do better in the next 40 years. Second, the outcome is quite sensitive to yield projections. An increase in yield growth of 0.4 percent percentage points can reverse projected price trends. Although this sounds like a relatively modest goal, these are exponential growth estimates (which must be maintained throughout the whole period) and require an increase of more than one-third in the current absolute yield growth rate. This cannot be taken for granted, especially because aggregate growth rates in both percentage and absolute terms are clearly in a declining phase (except for maize), and input growth may make a much smaller contribution than in the recent past. It should also be noted that the increase in demand for grains will be much greater to 2025 than for the following 25 years, so supply responses are needed relatively soon.

Sources of yield gains in the breadbaskets

This section reviews recent progress in grain yields through a series of case studies in some of the world's major breadbaskets. The full details of the case studies are reported elsewhere, in forthcoming work by Fischer and others, and only summary statistics are provided here.

The case studies indicate the depth of analysis that is necessary for understanding what is currently happening to crop yield on the farm (FY), which in turn is driven by: i) progress in potential yield (PY) arising from new agronomy and, increasingly, from new varieties; and ii) the adoption of new technologies that narrow the gap between FY and PY (expressed as a percentage of FY). The studies reveal considerable diversity among cases, based largely on crop species, agro-ecology and stage of economic development.

In all cases, PY and its rate of change were difficult to estimate, especially for crops under low to moderate rainfall (i.e., PY_W), because it is important that the PY or PY_W for a region comes from crops with the same natural resource endowment as the regional average. The estimates of current PY come from the latest breeders' trials, from simulation models calibrated using the latest cultivars, and sometimes, as a last resort, from yields in crop contests. Estimates of recent PY progress come from comparisons of historic sets of varieties grown inevitably under high inputs, preferably with disease and pest protection, as older varieties often become more susceptible over time. Progress is calculated simply by plotting yield against year of release for varieties released in the last 20 years or so; over this release period, relationships were always closer to linear than any other response shape. Note that this represents PY progress under advanced agronomy, and hence includes the genetic gains plus the usually significant gains from genotype-management interactions (Fischer, 2009). PY gains from agronomic innovation alone are thus not included. In advanced cropping systems, these are becoming a smaller factor in recent gains, although agronomic innovation remains very important for input use efficiency. In less developed systems, the lack of adoption of modern agronomy is often the major cause of the yield gap.

Finally, FY is usually obtained from official statistics, and sometimes from surveys. Yield progress for FY is not corrected for the effect of global CO_2

increase on C_3 crops mentioned earlier. However, PY growth estimated from trials of side-by-side comparisons of varieties of different vintages is not inflated by increased CO_2, and vintage-CO_2 interactions appear to be small where they have been studied.

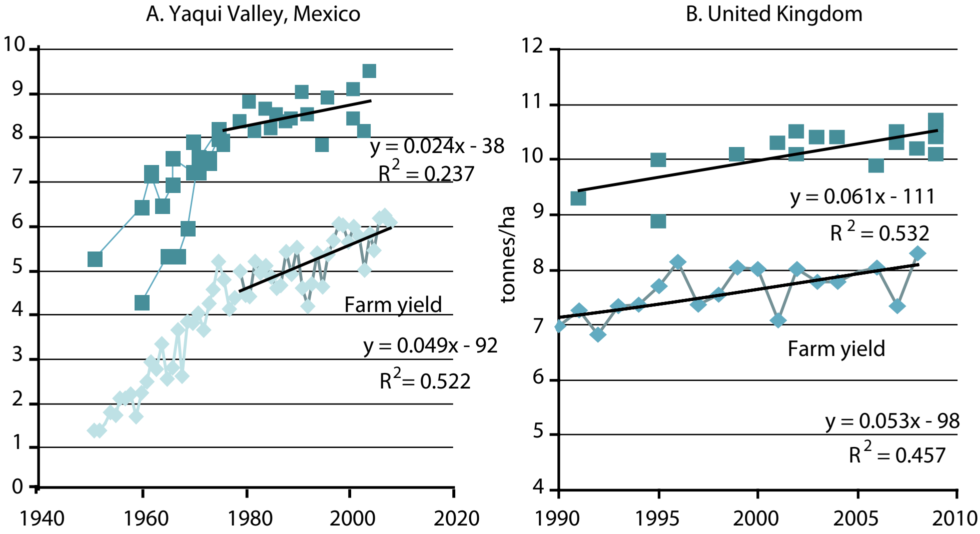
Several cases from each major crop environment and stage of economic development should be examined to obtain a proper sample and full understanding of what is behind the aggregate numbers on FY, and to project with some confidence. Some researchers are using high-resolution Geographic Information System (GIS) and crop modelling approaches to deal with the challenge of bringing together all of the world's cropping regions (e.g., the Harvest Choice programme that includes IFPRI). However, although more extensive sampling would bring benefits, the approach adopted in this chapter is an appropriate way forward, and case study numbers are bolstered from other sources of data wherever possible. For illustrative purposes, some key case studies are described more fully in the following subsections. This provides the basis for discussion of the two paths for increasing FY further: reducing the gap between FY and PY, and increasing PY.

Wheat

Figure 10.9 illustrates two of the better-documented case studies with wheat: the Yaqui Valley in Mexico is irrigated low-latitude spring wheat (S1, irrigated or high-rainfall spring wheat environment 1), which represents 22 percent of the world's wheat area, found almost entirely in the developing world; and the United Kingdom is a well-watered winter wheat environment (W1, winter wheat environment 1), representing 31 percent of the world's wheat area, three-quarters of which is in industrial nations (Heisey, Lantican and Dubin, 2002). The Yaqui Valley has been a major target for the wheat breeding programme of the International Maize and Wheat Improvement Center (CIMMYT) and its predecessor for more than 50 years; its environment is similar to that for wheat in Pakistan, northwest India, southern China and Egypt, all of which experienced a green revolution in wheat yields associated with improved varieties, irrigation and fertilizer. In the Yaqui Valley, variety turnover is rapid, and nitrogen (N) rates have now reached 260 kg per hectare. Despite this, FY progress has slowed to about 49 kg/ha/year over the last 30 years (Figure 10.9A), but this should be corrected downwards for a significant and surprising decline in average minimum temperatures over the period, giving progress of only 18 kg/ha/year, or 0.3 percent per year. This is exactly the rate of progress seen in PY determined at an experimental station in the centre of the valley. Thus the yield gap is fairly steady at 50 percent of FY, somewhat surprising for a region of moderately sized farms in a reasonably well developed agricultural system; current FY is at 6 tonnes/ha and PY at 9 tonnes/ha.

The United Kingdom has one of the highest national wheat yields (just over 8 tonnes/ha), with modern agriculture and an active private (breeding) and public research base. Excellent records of the Home Grown Cereal Authority (HGCA) from its protected variety experiments across the country give a good indication of PY. The rates of FY and PY progress have been fairly steady over the last 20 years, at 0.7 and 0.6 percent respectively; N use has been steady at 190 kg/ha for most of the period, and the yield gap is also steady (currently 25 percent of FY, and probably close to AYa, with little or no further gap to AYb in the United Kingdom today).

Figure 10.9
Changes in wheat PY and FY in the Yaqui Valley of Mexico and the United Kingdom



Potential yield is plotted against the year of variety release.

Sources: A – FY from Cajeme District Statistics; PY from numerous unpublished CIMMYT experiments collated by R.A. Fischer. B – FY from FAOSTAT; PY from HGCA.

Results for the Yaqui Valley, the United Kingdom and all other wheat cases are summarized in Table 10.2. In addition to S1 and W1, three other important wheat mega-environments are included.

Table 10.2 shows a diversity of combinations of key parameters for wheat growing regions. Two key observations are that average PY progress is only about 0.6 percent, and that only some yield gaps are closing. The actual gaps given (averaging 43 percent) can be compared with those in the review by Lobell, Cassman and Field (2009). For wheat, these authors were able to summarize

12 estimations from developing countries in the 1990s, showing a FY range of 40 to 95 percent of PY, averaging 65 percent: expressing the gap as a percentage of FY it averaged 55 percent, somewhat larger than the estimate for developing countries in Table 10.2. The difference with Table 10.2 could easily arise from both lower estimates for FY (understandable give the earlier dates to which FY refers, and the inclusion of less-advanced regions) and higher estimates for PY in the Lobell, Cassman and Field (2009) study.

Table 10.2
Summary statistics[a] from case studies of wheat yield change

		Yield and gap, 2007 or 2008			Current rate of change relative to 2008 yield or gap			Comments
Region and mega-environment[b]	Wheat area *(million ha)*	FY *(tonnes/ ha)*	FY *(tonnes/ ha)*	Gap *(% FY)*	PY *(%)*	PY *(%)*	Gap[c]	
Yaqui Valley S1	0.16	6.0	9.0	50	0.3	0.3	0	Case study
Punjab, India S1	3.9	4.3	6.25	45	0.2		0	Case study
Haryana, India S1	2.4	4.2	5.75	35	0.6		-	Case study
Egypt S1	1.2	6.5			1.6		--	High FY progress
Brazil S1	1.7	2.0			1.6		--	High FY progress
Western Australia S4	4.5	1.8	2.6d	45	1.4	0.5[d]	--	Case study
North Dakota, USA S6	3.4	2.5	3.7d	50	0.9	1.0[d]	0	Case study
UK W1	1.8	8.2	10.4	25	0.7	0.6	0	Case study
Eastern China W1	16	4.7?	7.0?	50		0.7		Zhou *et al.*, 2007a; 2007b
Kansas, USA W4	3.6	2.6	3.9[d]	45	0.6	0.4[d]	0	Case study

[a] All rates of FY change are from linear trends over last 20 to 30 years; 2008 yields are from the linear trends; no curvilinear fits were superior, unless noted. Where possible, FY trends have been corrected for secular weather change, but not for increasing CO$_2$. Blanks mean no data yet available.

[b] Mega-environments: S4 = low to moderate-rainfall spring wheat at low latitude, about 16 percent of world wheat area, equally distributed between industrial and developing countries; S6 = low to moderate-rainfall high-latitude spring wheat, 21 percent of world wheat area, mostly in industrial countries; and W4 = low to moderate-rainfall winter wheat, about 10 percent of world wheat area, equally distributed.

[c] + Increasing; 0 no change; -- decreasing.

[d] Actually PY_W.

Sources: FY and its change from FAOSTAT or United States Department of Agriculture (USDA) National Agricultural Statistics; PY from forthcoming work by Fischer and others, supplemented by reports from the literature.

S1 (irrigated and high-rainfall) is the most important wheat environment for the developing world. About 78 percent of the crop is irrigated, and was the first target of the green revolution. Several examples are given in Table 10.2. Progress in FY and PY have slowed markedly in Mexico and India (and South Asia in general), but Egypt, now exceeding the Yaqui Valley in yield, shows remarkable FY progress (discussed in the following subsection on rice), and high-rainfall countries such as Brazil also have good FY progress; acid soil tolerance and conservation tillage have been important factors in Brazil's progress.

The S4 environment characterizes rainfed wheat in the Mediterranean region, North Africa, West Asia, Australia and Argentina; it is probably the driest major wheat environment, with Western Australia – shown in Table 10.2 – providing an excellent example. It is the only mega-environment in which the yield gap has clearly closed lately, largely because of the adoption of many advances in wheat agronomy.

S6 is the high-latitude spring-sown wheat environment of the Northern Hemisphere, comprising 30 percent of the United States area, most of Canada, eastern parts of the Russian Federation and northern Kazakhstan, along with northeastern China. It is almost entirely rainfed and moderately dry. North Dakota, in the United States of America, fits S6 and shows modest progress and a yield gap fairly typical of rainfed wheat in the industrial world.

The United Kingdom, as already discussed, is probably reasonably representative of the favourable cool winter-habit W1 environment, comprising Europe, Ukraine, southern parts of the Russian Federation, the north China plain and the eastern United States.[7] In contrast, W4 refers to the drier cool wheat environments, dominated by the Great Plains of the United States, the Anatolian Plateau of Turkey and western China. It is represented in Table 10.2 by Kansas, whose low PY_W progress and modest yield gap are similar to those in rainfed Western Australia. FY progress would likely be similar or better in the W4 regions of Turkey and China because of the lower yield base; these regions would also have good scope for FY gains from increasing the currently low adoption of conservation tillage in this erosion-prone environment.

Rice

Figure 10.10 shows two case studies for rice, a crop that is almost entirely grown in developing countries (except for Japan, the Republic of Korea and the United States of America). Central Luzon in the Philippines includes the irrigated wet-season (I1, low-radiation) and dry-season (I2, high-radiation) tropical environments that dominate rice production, comprising about 54 percent of world rice area. Egypt represents irrigated rice in the very favourable intermediate-latitude high-radiation environment (I3), although this accounts for only 1 percent of the world's rice area, found equally in industrial and developing countries.

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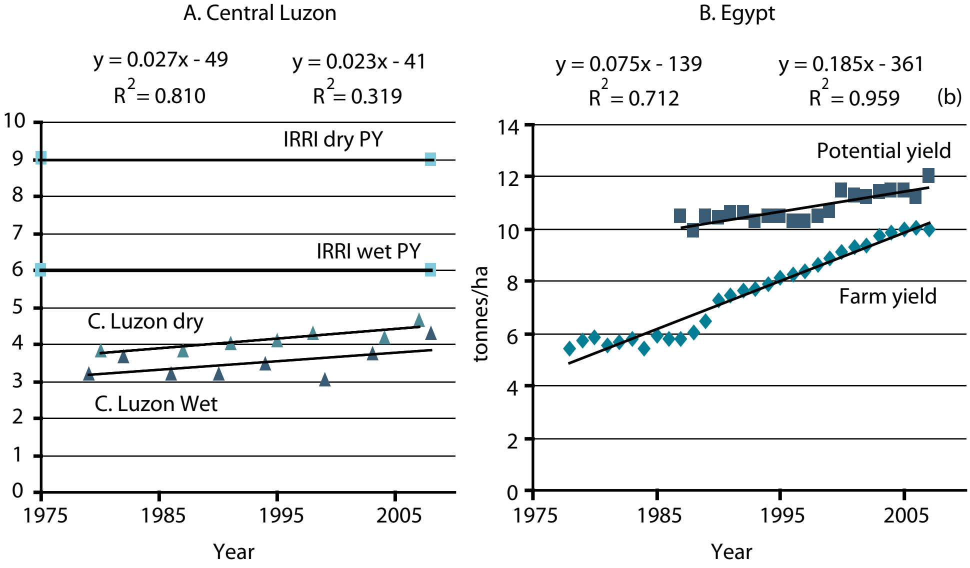
[7] Although the eastern Chinese portion may have lower PY because of warmer grain filling.

The International Rice Research Institute (IRRI) has regularly surveyed FY in Central Luzon over the last 50 years; variety turnover has been rapid, and over the last 30 years rice area has been entirely planted to modern varieties, reaching high levels of fertilizer application (150 kg/ha of N, phosphorus [P] and potassium [K]). After greater initial FY progress with the first modern varieties, yield progress since the late 1970s has been a steady 0.6 percent, and large gaps (60 percent wet season, 100 percent dry season) persist compared with PY at IRRI (Figure 10.10). The yield gap is smaller (about 35 percent) for wet-season crops in provinces adjacent to Central Luzon and at PhilRice (Laguna and Neuva Ecija), where FY progress has almost ceased. PY progress has been very slow (estimated at zero percent per annum) in Central Luzon, although varietal disease and insect resistance, earliness and quality have improved markedly (Peng *et al.*, 1999). The current dry-season PY of 9 tonnes/ha is corroborated by dry-season yields of 9 to 10 tonnes/ha for optimally managed irrigated rice in tropical America under the Latin American Fund for Irrigated Rice programme (G. Zorrilla, personal communication). These estimates do not include the new tropical hybrid varieties just reaching farmers in the Philippines and showing 11 to 14 percent increases in PY in the dry season (Yang *et al.*, 2007).

Figure 10.10
Changes in rice FY and PY in Central Luzon, dry season and wet season, and in Egypt



Sources: A – FY from IRRI surveys; PY from IRRI trials. B – FY from FAOSTAT; PY from on-farm demonstrations (A.E. Draz personal communication).

Egypt is noteworthy because of the contrast it represents: it has the highest FY in the world (10.1 tonnes/ha), exceeding that of California (of 9.4 tonnes/ha). FY has shown 1.8 percent annual growth in the last 20 years or so, while area has increased at 2 percent. PY is growing at only about 0.7 percent, meaning that there has been a marked closing of the yield gap, which is now about 15 percent of FY. It is suggested that the situation in Egypt reflects a strong research and extension effort; in addition, price reform in the late 1980s removed price disincentives for most crops, including rice. These and other case studies are summarized in Table 10.3.

Table 10.3
Summary statistics[a] from case studies of rice yield change in key regions

	Wheat area (million ha)	Yield and gap, 2007 or 2008			Current rate of change relative to 2008 yield or gap			Comments
Region and mega-environment[b]		FY (tonnes/ ha)	FY (tonnes/ ha)	Gap (% FY)	PY (%)	PY (%)	Gap[c]	
Central Luzon wet I1	0.8	3.8	6	60	0.6	0.2	0.0	
Punjab I1	2.4	3.8	8	110	0.9			
China I1	29.0	6.2			0.0			FY growth ceased 1996
Japan I1	3.0	6.5	10	55	0.3	0.4	-	Area decrease 1.7%
Central Luzon dry I2	0.4	4.5	9	100	0.6	0.2	0.0	
Egypt I3	0.7	10.1	11.6	15	1.8	0.7	--	Area increase 2%
California I3	0.2	9.4			0.0			
South Asia R1, R2, R3	28.5	1.8	3.6	100				IRRI, 2008

[a] All rates of FY change are from linear trends over the last 20 to 30 years; 2008 yields are from linear trends; no curvilinear fits were superior, unless noted. Blanks mean no data yet available.

[b] Mega-environments: R1 = rainfed lowland, 25 percent of global rice area; R2 = rainfed upland, 13 percent of global rice area; and R3 = deep-water, 7 percent of global rice area.

[c] + Increasing; 0 no change; -- decreasing.

Sources: FY and its change are average farm yield from FAOSTAT or USDA National Agricultural Statistics; PY from forthcoming work by Fischer and others, supplemented by reports from the literature.

The irrigated rice environment is well represented in Table 10.3. It was not possible to obtain reliable numbers for the other main rice ecologies – rainfed lowland (R1), rainfed upland (R2) and deep-water (R3) – but Table 10.3 attempts to cover aspects of these for South Asia. Notable in the table is the low FY growth, except for in Egypt, particularly the low or zero FY growth in China and Japan (and the Republic of Korea, but that is not shown). In China, this situation prevails, despite the 50 percent adoption of indica hybrids and the reporting of hybrid yields of up to 12 tonnes/ha in the rice bowl of the eastern China plains (Peng *et al.*, 2008). In Japan, eating quality requirements constrain FY. Also notable are the slow PY growth rates, and yield gaps are generally larger than with wheat, except for rice in Egypt.

The yield gaps in Table 10.3 can be compared with Lobell, Cassman and Field (2009), who summarize 41 estimates from developing countries of rice FY relative to PY: these range from 30 to 85 percent, with an average of 60 percent. This converts to a FY – PY gap of 65 percent. The authors supplement these numbers with results from a modelling exercise for irrigated rice PY across Asia, concluding that for northeast Asia, FY is about 75 percent of PY (gap = 35 percent of FY), but for northwest India it is only about 45 percent (gap = 120 percent).

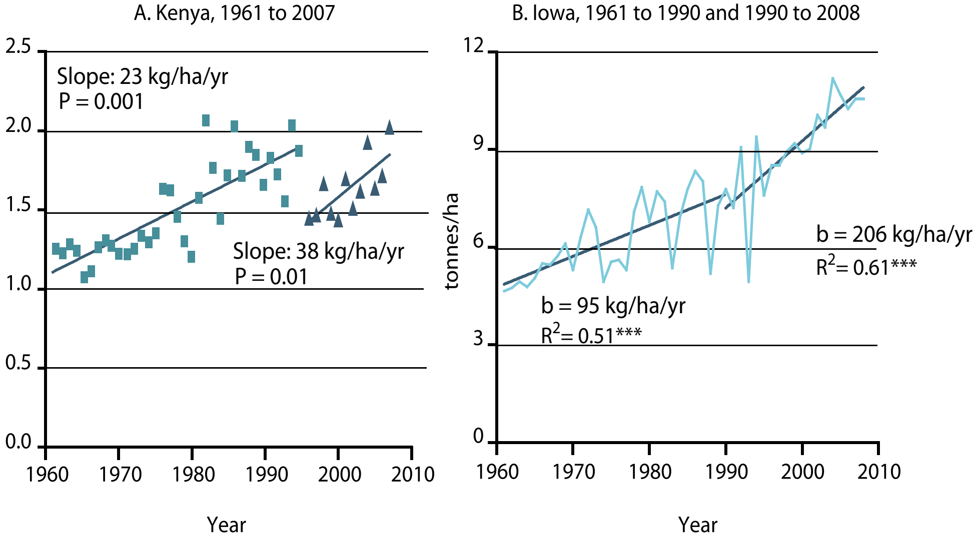
For rice, where irrigated environments are fairly distinctive and dominant, another estimate of yield gaps can be generated by simply comparing regional or national yields for similar crop agro-ecologies, and assuming that the highest yield represents the current global attainable yield (AY), or at least a conservative estimate of it. For example, based on Egypt, where the current national average yield for I3 is 10.1 tonnes/ha, 9 to 10 tonnes/ha can be seen as the appropriate AY for intermediate-latitude countries with relatively cloud-free summers and an absence of chilling at meiosis, such as experienced in the Islamic Republic of Iran (current yield 4.9 tonnes/ha), Uzbekistan (3.4 tonnes/ha) and Chile (5.5 tonnes/ha).

Maize and related crops

CIMMYT has defined useful mega-environments for maize in the developing world, to which the industrial countries were added for the case studies. The Kenya case study encompasses all the low-latitude maize environments: tropical-lowland (M1), accounting for 32 percent of world maize area; subtropical and mid-altitude (M2), with 13 percent of area; and highland (M3) with 4 percent. All of these are found in developing countries. Generally, these are relatively humid environments with maize tailored to fit the wet season, but – as maize is relatively susceptible to water shortage – drought stress is not uncommon. Heisey and Edmeades (1999) estimate 21 percent of the area in the tropics and 14 percent in the subtropics to be "often stressed". The second case study is of Iowa in the United States of America, representing the relatively humid (or supplementally irrigated) favourable temperate environment (M4), which contains 51 percent of the world's maize area, equally distributed between industrial and developing nations (with China dominating the latter).

Maize in Kenya is complicated because of the diverse environments, but 75 percent is in the more favourable M2 and M3 environments at more than 1 100 m above sea level. Kenya was a pioneer in hybrid maize and other farmer support, but this declined in the early 1980s, and yield growth ceased or even fell after 1980 (Fig 10.11A). In the 1990s, fertilizer supply was privatized, and fertilizer use has slowly grown to reach about 45 kg/ha (N + P + K); after falling in the early 1990s for no clear reason, FY appeared to start growing in the mid-1990s, averaging 38 kg/ha/year since 1996, to give an impressive 2.1 percent current growth rate (before the problems of 2008 when yield fell to 1.4 tonnes/ha). Regardless of whether the recent trend is cause for optimism, many factors still constrain maize yield in Kenya, including degraded soils; insufficient nutrient supply from both fertilizer and manure; risk associated with drought, especially in the marginal areas to which maize is spreading; weeds such as Striga; and intercropping, which is not in itself a constraint. Thus PY in the favoured M2 and M3 areas is still so far above FY (the yield gap nationally is at least 200 percent) as to seem irrelevant. However PY_W in less-favoured parts of Kenya is currently the focus of intensive conventional breeding efforts by CIMMYT and the International Institute of Tropical Agriculture (IITA), which have shown good progress in trials throughout Southern Africa (Bänziger *et al.*, 2006). Recently, genetic modification approaches for drought tolerance have been included.

Figure 10.11
Changes in maize farm yields in Kenya, and Iowa State, United States of America


A. Kenya, 1961 to 2007

B. Iowa, 1961 to 1990 and 1990 to 2008

Sources: A – yields from FAOSTAT. B – Iowa grain yields (14 percent moisture) from USDA National Agricultural Statistics www.nass.usda.gov/quickstats/pulldata_us.jsp.

Iowa State grows 5 million ha of maize, largely in one-crop per year rotation with soybeans. FY progress has been impressive for many years (Figure 10.11B); it accelerated around 1990, and from 1990 to 2007 averaged 206 kg/ha/year, or 2.0 percent from the impressive 10.5 tonnes/ha projected FY in 2009. This reflects a large investment in private sector breeding and public sector research, combined with modern farming and a favourable climate: it is also suggested that the recent spurt in progress commenced with the arrival of genetically modified maize varieties. Certainly, herbicide-resistant maize favours conservation tillage and, perhaps, earlier sowing, and *Bacillus thuringiensis* maize may be giving resistance against yield losses not even recognized in the past (e.g., root worm resistance). Estimates of PY are few, and estimates of its rate of change even fewer: farmer contests suggest that PY is currently about 17 tonnes/ha, which would give a yield gap of 60 percent, perhaps surprising for advanced farming. The best hybrids in breeders' and agronomists' trials appear to be reaching about 15 tonnes/ha. These same breeders indicate gains in PY of about 100 to 200 kg/ha/year, or about 1.0 percent per annum (e.g., Hammer *et al.*, 2009; Edgerton, 2009), but this important number merits further study.

Table 10.4
Summary statistics[a] for case studies of maize yield change in key regions, and for related crops

		Yield and gap, 2007 or 2008			Current rate of change relative to 2008 yield or gap			
Region and mega-environment[b]	Wheat area *(million ha)*	FY *(tonnes/ha)*	FY *(tonnes/ha)*	Gap *(% FY)*	PY *(%)*	PY *(%)*	Gap[c]	Comments
Kenya M1, M2, M3	1.75	1.8	6[b]	200+ [b]	2.1	++	--	FY growth in last 12 years only
Sub-Saharan Africa M1, M2, M3		1.6	4.1[c]	193[c]	0.8			Area increases
Brazil M2	12.5	3.6			2.6			
Iowa, USA M4	5.3	10.5	15	43	2.0	1.0	--	PY from trials versus contests
USA M4	32	9.7			1.5			
China M4	27	5.3			1.0			Area growth 1.4%
Egypt M4	0.8	8.4			2.0			
Other crops								
Sorghum Africa M2	27	1.0			0.4			Area growth 1.7%
Millet Africa M2	22	0.8			1.0			Area growth 1.3%
Millet India M2	11	0.9	1.8	100	1.7			Area decline -2.0%
Soybeans Brazil M2	21	2.7			1.7	0.7		Area growth 4.4%
Soybeans USA M4	31	2.8	3.6	30	1.0	0.7		Area growth 1.5%

[a] All rates of FY change are from linear trends over the last 20 years; 2008 yields are from linear trends; no curvilinear fits were superior, unless noted.

[b] Conservative expert opinion for PY across all environments.

[c] AY from on-farm with best-bet technologies (Sasakawa global 2000 reports).

[d] + Increasing; 0 no change; -- decreasing.

Sources: FY from FAOSTAT or United States Department of Agriculture (USDA) National Agricultural Statistics.

These maize case studies and other useful maize data are summarized in Table 10.4, which also includes sorghum, millet and soybean data. Sorghum and millet are the poor cousins of maize, tending to grow on the margins of maize areas where it is too dry for maize. Soybean, on the other hand, is a unique leguminous oilseed that, unlike cereals, has shown strong area growth in the last decades.

Notable in Table 10.4 are the relatively high maize FY growth rates compared with wheat and rice, not only in Brazil, the United States of America, China and Egypt, where hybrids dominate, but also with some growth in sub-Saharan Africa. Growth in sub-Saharan Africa is from a very low base, as yield gaps remain huge. Egypt since the early 1990s shows what can be achieved in a well-endowed environment with good policy on research, extension and prices.

Again the maize gaps in Table 10.4 can be compared with those in the extensive review by Lobell, Cassman and Field (2009), who cite nine tropical and subtropical maize cases (with FY ranging from 16 to 46 percent of PY, and averaging 33 percent) and two reports from Nebraska: irrigated (56 percent) and rainfed (40 percent). These convert into gaps of 200 percent of FY in the tropics and subtropics, 85 percent in Nebraska irrigated, and 150 percent in Nebraska rainfed. These numbers are quite comparable with those in Table 10.4, and suggest that yield gaps are larger for maize than for wheat and rice. However, the Nebraska data are surprising, and come originally from Duvick and Cassman (1999). Lobell, Cassman and Field (2009) later cite unpublished simulations of maize PY, which indicate that FYs in Nebraska are 75 percent (irrigated) and 65 percent (rainfed) of PY, amounting to gaps of only 35 percent (irrigated) and 55 percent (rainfed) of PY.[8]

In another approach, the poor yields in M1, M2 and M3 environments in sub-Saharan Africa in Table 10.4 can be contrasted with yields in relatively similar environments in Southeast Asia, averaging more than 3 tonnes/ha across 8 million ha, and Brazil, of 3.6 tonnes/ha.

Yields of sorghum and millet in sub-Saharan Africa are even poorer than those of maize, probably partly reflecting area expansion into more marginal areas. In India, millet is the target of the International Crop Research Institute for the Semi-Arid Tropics' (ICRISAT's) research effort: yield grows but area declines, while recent simulation modelling and on-farm demonstrations indicate PY to be 1.8 tonnes/ha, suggesting a gap of 100 percent (Murty *et al.*, 2007).

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[8] The discrepancy with the Duvick and Cassman (1999) report comes from the lower values of PY, derived from simulation in the later report (e.g., ranging from 12.2 to 17.6 tonnes/ha across Nebraska, irrigated). In addition, compared with the estimate of PY from contests in adjacent Iowa (15 tonnes/ha; Table 10.4) and current yields of contest-winning crops in Nebraska, these simulations seem unrealistically low, so the view that there is a moderate yield gap even in Nebraska, and even with irrigated maize, holds.

Soybean is showing remarkable yield and area growth globally, exemplified by Brazil and the United States of America; it is grown in maize environments, often in rotation with maize.

Summary of yield progress and yield gaps

In the wheat and rice examples, FY progress is generally below 1.5 percent, and usually below 1.0 percent. PY progress from breeding is no more than 1.0 percent, and often much less for wheat and rice, crops where breeders must give more attention to grain quality traits and disease resistance than for maize. In most situations, there is a gap exceeding 30 percent between FY and PY, but this reaches 100 percent in several rice cases. The rate of gap closing has been slow, except in the case of rice in Egypt. For maize, FY progress is often 1.5 percent or better. It has been difficult to obtain good estimates of PY progress for maize, but it likely exceeds that of wheat and rice, probably reflecting fewer selection constraints and the high involvement of hybrids and the private sector. The gap between FY and PY in maize is large in sub-Saharan Africa, where it easily exceeds 100 percent, but is only moderate and is closing in Iowa.

Closing existing yield gaps

Yield gaps exist because known technologies that can be applied at the local experiment station are not applied in farmers' fields with the same natural resource endowments. There are many reasons for this, but the first to consider are economics and risk aversion, about which there is a rich literature. Farm yields (FYs) that are constrained only by such considerations have usefully been defined as the attainable yield (AY, see section on Defining key concepts), but it must be borne in mind that AY is driven by farm-gate prices, which may be distorted from world prices by subsidies, taxes or poor infrastructure and institutions. Of the examples studied in the previous section, wheat yields in the United Kingdom – which has modern farmers, institutions and infrastructure, and minimal subsidies – should approach AY: the 25 percent yield gap between FY and PY (Table 10.2) is therefore a useful estimate of the minimum gap to be expected due to economics and risk. Another approach to calculating AY is to look at the distribution of field yields within a region and assume that some proportion of the higher yields indicates the AY, for example, the ninth decile (Yaqui Valley case study). However, this has problems: it is hard to obtain a large unbiased sample of field yields; and yield variation may be due to variation in the natural resource base of the fields, not solely to that in exploitable factors.

In the case studies, only one yield gap smaller than that for wheat in the United Kingdom was found – 15 percent for rice in Egypt. In Egypt, there appears to be no large price subsidy, but there is an especially strong and focused research and extension effort for rice, which is highly concentrated in the Nile Delta region. It is interesting that Lobell, Cassman and Field (2009) also suggest that a gap of 25 percent of FY may represent the economically optimum level of production, while recognizing that risk and uncertainty in farmers' decision-making (especially in rainfed situations) may raise the estimate of this yield gap somewhat. Taking a conservative 30 percent as the minimum above which there is scope for economic exploitation, 14 of the 17 cases outlined in the previous section appear to have exploitable gaps, some being quite large, notably maize in sub-Saharan Africa. As might be expected, there is also a strong tendency for smaller gaps in industrial countries. Other things being equal, PY increases might be expected to be important for the future where the gap is small, and gap closing possibilities to increase as the size of the gap increases. This section looks at gap closing.

Constraints contributing to yield gaps

Poor infrastructure, weak institutions and bad farm policy can create huge obstacles to the adoption of improved technologies. These obstacles are exhibited particularly in price disincentives at the farm-gate, expensive credit and increased risk in general; for example, the N-to-grain fertilizer price ratio in much of Africa is on average double that in other regions, and higher still in inland land-locked regions (Morris *et al.*, 2007). Solutions lie with public investment in infrastructure and institutions, and with sound policy, the lack of which has been a major contributor to the large yield gap in places such as sub-Saharan Africa (e.g., Table 10.4). These are widely canvassed in other chapters; this section focuses on those other (non-market) constraints that contribute to the exploitable yield gap (the Agronomic column of Table 10.5).

The Breeding column in Table 10.5 points to ways in which targeted breeding can help close the yield gaps arising from given constraints, not by raising PY or PY_W, but essentially by making varieties more resilient: new varieties are generally adopted more readily than new management techniques, often because they are a less expensive option for the farmer and the extension organization, so this is always a favoured route if the required genetic variation exists. In contrast to breeding, there is nothing new in the other two Resolution columns of Table 10.5; these technologies and policies already exist in many parts of the world (although some might be refined with further research, such as information technology for smallholders, or seasonal forecasting) and all have had or should have positive impacts on FY where appropriate.

Table 10.5
Constraining factors contributing to the FY – PY gap, and ways of resolving them

	Resolution[a]		
Constraint	Argonomic	Breeding	Institutional/ infrastructural
General farmer constraints			
Lack of farmer awareness, conviction or skill	On-farm demonstration	On-farm testing and selection	Education, media campaigns, extension
Farmer risk aversion	Forecasts, tactical decision-making, e.g., for N top-dressing	Tolerance of extreme weather events, e.g., drought, flooding, hail, frost, wind	Insurance, favourable credit terms
Inadequate labour supply	Mechanization, reduced tillage, herbicides	Selection for uniform maturity to favour mechanical harvesting	Facilitated labour migration; credit for mechanization
Technical constraints			
Lack of major long-term soil amelioration	Drainage, land levelling, liming, deep tillage, gypsum	Waterlogging and salt tolerance	Long-term credit
Excess tillage and loss of moisture, soil compaction	Conservation tillage options and suitable machinery, controlled traffic	Suitable varieties; disease and herbicide tolerance	Credit for new machinery
Manageable topsoil toxicities	Amelioration, e.g., lime for acidity	Acid tolerance	Input suppliers, credit
Sub-optimal nutrient supply	Diagnostics, application of nutrients, tactics	Some scope for improved N, P and zinc uptake and utilization	Input suppliers, quality control
Soil variation within and between adjacent fields	Diagnostics for adjustment of application rates	Greater tolerance of soil stresses	
Use of old varieties or poor seed	Better on-farm seed management and storage	F1 hybrids and licensed traits to encourage strong seed industry	Strong seed industry and regulation, credit
Incorrect time of sowing	Mechanization and reduced tillage to accelerate sowing	Varieties with a range of maturities; herbicide-tolerant varieties	Policy for favouring mechanization, contract seeding
Poor plant population	Better drilling procedures and machines, quality seed storage	More robust varieties, e.g., long coleoptile in wheat, more tillage	Strong seed industry
Diseases and pests, above and below ground	Biocides, sanitation, crop rotation	Host plant resistance	Input suppliers, quality control
Weeds	Herbicides, cultivation, sanitation, crop rotation	Enhanced crop plant competitiveness, herbicide tolerance	Herbicide quality control, release regulation
Poor water management in irrigated systems	Improved water application techniques and skills	Greater tolerance to water shortage and excess	Efficient supply systems to farms
Long-term soil degradation	Crop rotation, fertilizer, green manuring, farmyard manure, conservation tillage, zero tillage	Varieties adapted to biotic and abiotic stresses of high plant residue levels, and with good residue production	Regulations ensuring farmers' landownership

[a] Resolution to allow FY to approach the AY corresponding to current PY with realistic economics.

Without doubt, plant breeding's major role in gap closing lies in host plant resistance. Oerke (2006) presented a meta-analysis of actual global yield losses due to biotic stress (weeds, insects, fungi, bacteria and viruses), which averaged more than 23 percent of estimated AY (hence a greater percentage of FY) across the major cereals (without any controls, potential losses were estimated to average 32 percent) (Table 10.6). This is part of the exploitable yield gap, and its reduction is the aim of host plant resistance breeding. Conventional breeding is protecting progress by maintaining resistance levels in the face of evolving pest agents, while aiming to make progress by strengthening resistances, especially through exploiting durable sources of resistance. This has recently been documented globally for the case of wheat rusts (Dubin and Brennan, 2009). Others have pointed to the growing impact of transgenic insect resistance, particularly with maize (and cotton), and linked it to yield gains as more effective, less expensive host plant resistance replaces insecticides, which were often not 100 percent effective. It would seem that the scope for using better host plant resistance to halve a portion of the global yield gap – which is about 30 percent of FY and due to biotic stresses – is good in the medium term (15 years), especially if transgenic resistance to fungal diseases, which currently exists in a few cases, can be delivered.

Table 10.6
Global estimates of potential crop losses without physical, biological or chemical protection, and actual crop losses

	Potential losses *(% of AY)*			Actual losses *(% of AY)*		
Biotic stress agent	Wheat	Rice	Maize	Wheat	Rice	Maize
Weeds	23.0	37.1	40.3	7.7	10.2	10.5
Animal pests	8.7	24.7	15.9	7.9	15.1	9.6
Pathogens	15.6	13.5	9.4	10.2	10.8	8.5
Virus	2.5	1.7	2.9	2.4	1.4	2.7
Total	49.8	77.0	68.5	28.2	37.4	31.2

Source: Oerke, 2006.

The Oerke (2006) meta-analysis also estimates actual losses due to weeds at 10 percent (with potential losses of 33 percent). Modern varieties tend to be more susceptible to weed competition, so breeding did not help until the advent of herbicide-tolerant cultivars, first using natural resistance, and then in the last 15 years resistance based on genetic modification. Gyphosate- ("round-up") and glufosinate-resistant genetically modified varieties have been very successful in maize, soybean and canola in the Americas, facilitating weed control, conservation tillage and often earlier planting, all leading to somewhat higher yields. Genetically modified herbicide resistance will undoubtedly spread into the rest of the world, but integrated weed management, employing a suite of agronomic and breeding approaches will remain vital for sustainable weed control, and will be a special challenge for extension in developing countries.

Prioritizing constraints and reaching farmers

There are usually multiple constraints in any situation, and it is a challenge determining which constraints are more critical and more amenable to change while recognizing that interventions often interact positively and are thus most effective when adopted together (de Wit, 1992). This can only be achieved by on-farm survey and experimentation, which started many years ago with farming systems research, farm management clubs and rapid rural appraisal, and continues in many guises in the industrial world, especially influenced by the privatization of agricultural extension and the use of advances in remote sensing and information and communication technology. It is noteworthy that large commercial maize seed companies in the industrial world, such as Monsanto and Pioneer, employ more agronomy extensionists than breeders to ensure that new varieties reach their potential in farmers' fields.

In the developing world, more traditional approaches remain, although with growing emphasis on farmer participation (Paroda, 2004). Lobell, Cassman and Field (2009) recount how IRRI conducted on-farm rice experiments in Asia in the 1970s to test high inputs, and learned that FY varied greatly, as did responses to inputs, especially fertilizer and insecticide, which were often uneconomic. This pointed to the importance of field-to-field variability, and the need to adjust inputs accordingly and throughout the season, whether by site-specific nutrient management, which reached maturity some 20 years later (Dobermann *et al.*, 2002), or via field-level pest monitoring as part of integrated pest management packages. Another lesson is that this is scientist-intensive and expensive research, often taken over by farmers and their advisers in the industrial world, and explaining why large yield gaps often persist in developing countries, where circumstances demand innovative approaches to reach the billion small farmers (e.g., Paroda, 2004). However, there are also cases of unique progress, as demonstrated by the almost instantaneous delivery of field-specific recommendations to small farmers in the Philippines through the ubiquitous mobile phone (Roland Buresh, personal communication).

Very recently, IRRI re-examined rice yield gaps, this time using expert knowledge to assess constraints and possibilities for irrigated rice in South Asia (IRRI, 2008). For this crop, FY is currently 5.1 tonnes/ha on 34.3 million ha; it was estimated that yield was constrained to an average of 1.9 tonnes/ha

(37 percent) by yield-limiting factors including nutrients (10 percent), diseases (7 percent), weeds (7 percent), water shortage (5 percent) and rats (4 percent). IRRI predicted that the adoption of existing technology and ongoing breeding for robustness would reduce the total loss by about one-third over the next 15 years, increasing FY by 35 kg/ha, or 0.7 percent, per year. The exercise was repeated for the 28.5 million ha of rainfed lowland and upland rice in South Asia, with a current FY of 1.8 tonnes/ha. Yield-limiting factors amounted to 68 percent of FY, including nutrients (23 percent), disease (15 percent) and weeds (12 percent); about one-quarter of these losses are predicted to be eliminated by research for development, including extension, over the next 15 years, adding 19 kg/ha, or 1.0 percent, per year to FY. With this background on South Asia, IRRI – along with National Agricultural Research Systems (NARS), the Consultative Group on International Agricultural Research (CGIAR) and private sector partners – has recently embarked on a new extension approach, the Cereal Systems Initiative for South Asia. This primarily involves hubs staffed by experts mandated to adapt and deliver existing technologies to local farmers.

For wheat in the Yaqui Valley, a recent concerted effort has been made to understand the yield gap PY – FY (currently 50 percent) (Table 10.2), using the latest high-resolution satellite imagery to estimate field-level yields (Lobell *et al.*, 2003) and supplement a long history of farm surveys. From images over several years, it was estimated that wheat yields were constrained by late planting (Ortiz-Monasterio and Lobell, 2007), delays in the first post-plant irrigation (Lobell and Ortiz-Monasterio, 2008) and summer fallow weeds (Ortiz-Monasterio and Lobell, 2007). Improved institutions and farm management decisions could largely eliminate these constraints (which averaged a total of about 10 to 15 percent of FY a year), and would bridge about half of the gap to estimated AY in the valley. It is interesting that N nutrition was only a very minor limitation, surveys and on-farm fieldwork pointing to considerable scope for better N management to improve N fertilizer use efficiency, if not increase yield (Ortiz-Monasterio and Raun, 2007).

The persistence of large yield gaps, especially in the developing world, draws attention to situations where these gaps have been closed. As already mentioned, rice in Egypt is an obvious example. A second example of dramatic technology adoption, albeit with less immediate implications for FY than for sustainability of the whole cropping system, relates to the uptake of conservation tillage for wheat, maize and soybeans in southern South America (Argentina, Brazil and Paraguay), which rose from zero in 1970 to 24 million ha in 2000. This was very much driven by farmers' groups and farmers themselves, faced with the threat of serious soil degradation and the opportunity provided by knock-down herbicides and knowledge spill-over from the North (e.g., Ekboir, 2002). This revolution has yet to reach other developing continents, but is beginning in northwest South Asia. A third success story among poor small farmers has recently emerged from winter maize in northeastern India and Bangladesh.

Conclusions on gap closing

Despite individual success stories such as rice in Egypt, yield gaps generally appear to be persistent and to close only slowly; this is the case even for gaps that are well above those expected for the economics and risk aversion concerned, and even when PY progress has slowed so that catch-up through eliminating excessive lags in varietal adoption is not a major issue. The problem is that gap closing on the large scale needed requires massive investments in rural infrastructure and institutions, as well as technology transfer, and these are not forthcoming, as exemplified by maize in sub-Saharan Africa.[9] Elsewhere, public sector agencies, particularly those reaching the billion small farmers in Asia (Paroda, 2004), aided by the private sector, particularly in Latin America, have made some inroads on the yield gap; they should continue to do so in proportion to the investments made, but there is also scope for innovation, for example based on modern information and communication technologies (see previous subsection and the section on Prices, efficiency, productivity and R&D investment). The employment of agronomists by private seed companies is a pattern that is bound to be followed in the developing world as its seed industry grows in strength and competitiveness. With gap closing, there are no spill-ins as there are in the case of PY advances through R&D; developments need to be made locally, but it can be argued that the Internet and mobile phones are relevant spill-in technologies whose role could greatly expand. Given the persistence of yield gaps, it remains critically important to continue to lift FY through improved PY, the subject of the next section.

Increasing yield potential

As described in previous sections, PY has grown substantially in the past, through breeding backed by improved agronomy, and this has driven FY growth. Earlier discussion suggests that in the future, growth in PY is probably going to depend more on breeding than on new developments in crop agronomy. New management through breeding synergies will certainly be discovered but is difficult to anticipate. There is a sense that genetic variation for yield must, at some time, become exhausted, and that the relatively easy improvements, such as

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[9] The first comprehensive report on the African Millennium Village Project (Nziguheba *et al.*, 2010) offers useful and encouraging insights into this key issue.

increases in harvest index (HI)[10] and adaptation of phenology, have already been made. Progress will probably depend increasingly on molecular and physiological knowledge of plant growth processes to improve the targeting of breeding efforts for PY, although empirical breeding continues to make some yield progress. This section considers the prospects and avenues for increased PY, under conditions of adequate water and of water constraint (PY_W). Brief mention is also made of PY under N limitations.

Components of PY

Crop physiologists have developed useful analytical frameworks for exploring potential grain yield and its components under radiation- or water-limited conditions (Monteith, 1977; Passioura, 1977):

$$PY = \text{total above-ground dry weight (TDW) x HI} \qquad (1)$$
$$PY = \int PAR_i \text{ x RUE x HI} \qquad (2)$$
$$PY_W = \text{transpiration (T) x TE x HI} \qquad (3)$$

where $\int PAR_i$ is the integral of photosynthetically-active radiation (PAR, MJ)[11] intercepted by green tissue over the life of the crop; and RUE, or radiation use efficiency, is the efficiency with which PAR_i is converted into above-ground biomass (in grams per megajoule [g/MJ]). For PY_W, T is the amount of water taken up and transpired by the plant (in millimetres [mm]);[12] and TE is transpiration efficiency for creating dry weight (milligrams per gram, or kilograms per hectare per millimetre). A parallel to equation (3) for PY_N, N-limited potential yield, can be written as N absorbed and NUE (nitrogen use efficiency). There are many variations of these identities (Mitchell, Sheehy and Woodward, 1998), but they all point towards the efficiency with which a limiting input (radiation, water, N) is captured and used to create dry weight, and how efficiently the biomass is converted to grain (HI). The concept of PY per day is also important; in tropical rice, for example, PY has remained static, while varieties have become earlier, resulting in a gain in PY/day (Peng *et al.*, 1999).

Progress in PY through agronomy has largely come through better crop nutrition, especially N nutrition, giving greater leaf area of longer duration, hence

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[10] The HI is the ratio of the grain yield to total biomass at maturity.

[11] Crop physiologists work with either total solar radiation or PAR, the latter being close to 0.5 times the former wherever sunshine is involved (Mitchell, Sheehy and Woodward, 1998); this chapter uses PAR throughout.

[12] Throughout this chapter, mm refers to rainfall or water use in depth of water over the land surface; thus for 1 ha, 1 mm equals $10m^3$.

increased PAR_i, and modest increases in RUE (Muchow and Sinclair, 1994; Bange, Hammer and Rickert, 1997). Altered planting date, especially earlier planting, can also give small gains in PY and PY_W through better crop timing with respect to expected weather patterns. Altered planting configuration can give earlier full radiation capture and more even radiation distribution among plants, both important for PY. Progress in breeding for increased PY over the past 50 years has been very significant, and is generally attributed to increases in HI, often via shorter stature in wheat, rice and tropical maize (e.g., Johnson *et al.*, 1986). An exception is temperate maize adapted to the United States of America or Argentina, where PY has increased because TDW has increased, while HI has remained relatively high and stable (Duvick, 2005). Typical values of HI are 0.5 to 0.55 under good conditions for modern winter wheat, rice and temperate maize varieties, but only 0.4 to 0.45 for spring wheat and modern tropical maize varieties (Johnston *et al.*, 1986; Duvick, Smith and Cooper, 2004). There appears little scope for further increase in HI beyond 0.5 because the crop needs a stable structure to distribute its leaf area, support its seeds and prevent lodging. However, there seems to be scope for a 20 percent increase in HI in spring wheat and tropical maize.

The increase in TDW in temperate maize appears to be related to a number of small changes: more erect leaves, which should give higher RUE; more grains per square metre at high planting density, meaning greater sink strength and RUE during grain filling; greater “stay-green”, meaning more PAR_i in late grain filling; and a general improvement in tolerance to minor stresses such as cool nights, sudden changes in radiation, high plant density and oxidative chemicals (Tollenaar and Wu, 1999; Duvick and Cassman, 1999).[13] More recently, early cold tolerance, permitting earlier planting, has been highlighted (Kucharik, 2008), and Hammer *et al.* (2009) have made the very novel proposition, supported largely by modelling, that modern hybrids are apparently generating more biomass by capturing and transpiring about 270 mm of additional water from deeper in the soil than their counterparts of 70 years ago. In the case of wheat and rice, however, TDW has increased relatively little through breeding, although there are some reports of increased RUE (see following subsection).

A key aspect of gains in PY in the past has been increased numbers of grains per square metre of land area, rather than changes in weight of individual grains

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[13] Duvick and Cassman (1999) argue that even under irrigation and excellent management, apparently minor but common stresses such as cool nights, sudden changes in radiation as clouds move over the sun, and occasional high temperature are important. They conclude that yield gains with selection have come about because of better tolerance to these “minor stresses”, rather than because of increase in yield potential *per se*. At modern densities (about 100 000 plants/ha), plants are also under substantial stress from crowding.

(e.g., Bolaños and Edmeades, 1996; Fischer, 2007). Seed number per square metre is related to crop growth rate from 20 to 30 days before flowering to ten days after flowering in all three cereals (see later), and to the variety's ability to partition assimilate to the developing ear (Andrade, Otegui and Vega, 2000; Shearman *et al.*, 2005). Rice and wheat varieties with the highest PY appear also to accumulate and later translocate larger amounts of temporarily stored pre-anthesis carbohydrate to the grain (Shearman *et al.*, 2005; Katsura *et al.*, 2007). Grains that are set at flowering must be filled adequately from current assimilate plus stored carbohydrate, and adequate water and N nutrition are essential (Wolfe *et al.*, 1988).

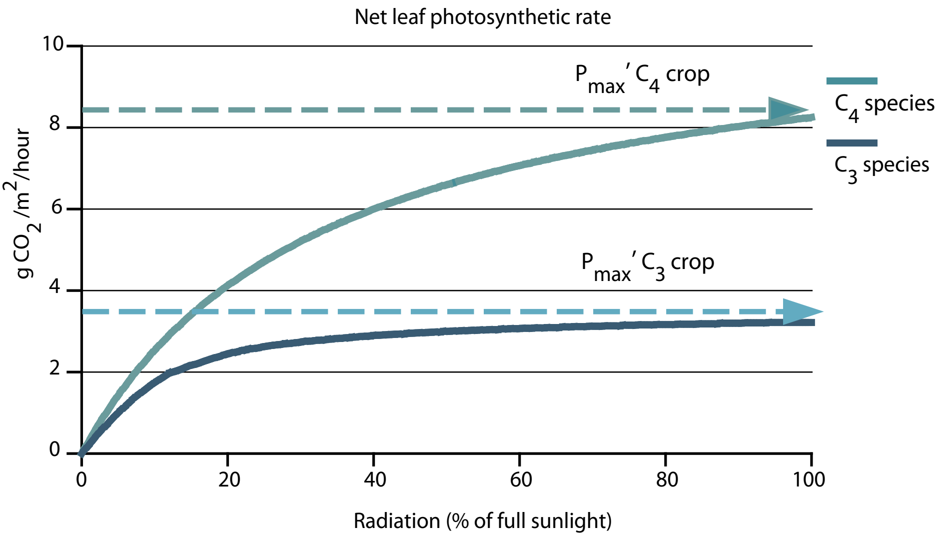
In summary, the likeliest routes for further increases in PY are through increases in RUE or PAR_i by boosting photosynthetic activity and/or extending the active life of leaves, while for PY_W, preventing the common decline in HI when crops are under stress, especially around flowering, is also an important possibility. The challenge of RUE and its constituent components attracts many plant scientists. To quote Duvick (2005) "Finally … maize breeders can always hope for the Holy Grail of plant physiologists, major [increases in RUE], effected without disrupting the rest of the infinitely complicated network of interacting genetic systems".

Increasing radiation use efficiency

RUE is the ratio of gross photosynthesis minus (crop respiration + root dry matter) to radiation intercepted over periods that range from a few days to the crop's complete lifetime. RUE was initially found to be a relatively stable number and a useful integrator across leaf positions and radiation levels (Mitchell, Sheehy and Woodward, 1998). Crops differ in their photosynthetic systems. Maize has a C_4 photosynthetic system that allows its leaves to respond to higher levels of irradiance than the C_3 system of wheat and rice, but performs poorly in cool conditions. The C_4 system has a CO_2-concentrating mechanism in bundle sheath cells (the so-called Kranz anatomy) that sharply reduces CO_2 losses from the photorespiration observed in C_3 crops. As irradiance of the leaf increases, the photosynthetic rate of C_3 species reaches a maximum (P_{max}) at a lower irradiance and a lower value of photosynthesis than that of C_4 species; a C_3 species therefore has lower RUE (Figure 10.12), TE and NUE than a C_4 species. However, C_3 species are generally better adapted to cooler conditions.

The main source of variation in RUE is among the species themselves, and P_{max} and RUE are positively associated. Although RUE increases less than a given relative increase in P_{max}, the exact relationship depends on how light is distributed down into the canopy. Mitchell, Sheehy and Woodward (1998) found that the average RUE values during vegetative growth under optimal conditions were 2.7 g/MJ for wheat, 2.2 g/MJ for rice, 3.3g/MJ for maize, and 1.9 g/MJ for soybean, and varietal differences in RUE within crops are quite small. More recent evaluations of RUE in modern maize hybrids result in a value of 3.8 g/MJ, suggesting a possible increase in RUE had occurred with selection (Lindquist *et al.*, 2005). However, selection specifically for higher leaf photosynthetic rate in several past studies, although sometimes successful, has failed to raise crop yield (Crosbie and Pearce, 1982; Austin, 1989; Evans, 1993). Nevertheless, Long *et al.* (2006) suggest theoretical maximum limits to RUE of 5.8 g/MJ for C_3 crops, and 6.9 g/MJ for C_4 crops.

Figure 10.12
Response of leaf net photosynthetic rate to radiation as a proportion of full sunlight for C_3 and C_4 species



Source: Loomis and Connor, 1992.

As leaves spend much of their lives in shade, the likely route to improving PY is to increase RUE under radiation levels of 10 to 50 percent full radiation (Figure 10.12). RUE values of 3.9 g/MJ for rice (Katsura *et al.*, 2007) and 7.6 g/MJ for maize (Tollenaar and Wu, 1999) grown under low radiation conditions support this contention. Most modern cereal varieties have erect leaves and a high ratio of leaf area to ground area. This results in lower irradiance at the leaf surface, and hence a higher RUE, but there is little scope for further improving RUE via canopy structure in these crops, because all the modern varieties have very erect leaves. Loomis and Amthor (1999) also conclude that crop respiration is very efficient, with only modest prospects of improvement through targeted selection for low respiration rates.

Future increases in RUE via breeding are therefore likely to be through increases in P_{max}; recent evidence suggests that P_{max} is higher in modern varieties of wheat (Fischer *et al.*, 1998) and rice (Horie *et al.*, 2003), while it has been shown in the United Kingdom that modern varieties of winter wheat have higher RUE; this progress in photosynthesis was measured during the critical period determining seed number. What kind of additional progress could be made by focusing on P_{max} itself? One opportunity for dramatic changes in P_{max} lies in genetic engineering of the leaf photosynthetic system, especially the central photosynthetic enzyme, Rubisco, by increasing its efficiency in capturing CO_2, or increasing the supply of CO_2 or other limiting substrates to the enzyme. A very ambitious project under way at IRRI involves genetic engineering of the C_4 pathway into C_3 crop rice to improve CO_2 supply to Rubisco. Long *et al.* (2006) predict RUE increases at annual rates of 1 to 4 percent over the next ten to 20 years through mechanisms such as these. Other strategies include reducing photorespiration in C_3 crops or reducing the thermal sensitivity of Rubisco activase by gene shuffling so that Rubisco remains active at higher temperatures (Salvucci, 2008). However, these transgenic approaches may have a low chance of success in the medium term because of the complexity of the tasks involved. A less challenging approach could involve a search, for example among primitive wheats and wild relatives, for more efficient photosynthetic machinery, bearing in mind that such wheats have already exhibited higher P_{max} levels than modern varieties (Evans, 1993).

Projections of potential yields

Wheat: A well-researched estimate of wheat PY for the United Kingdom (Sylvester-Bradley, Foulkes and Reynolds, 2005; R. Sylvester-Bradley personal communication) – based on reasonable assumptions, including an RUE of 2.8 g/MJ and an HI of 0.6, while deploying stem dry matter as efficiently as possible to minimize lodging risk – resulted in 19 tonnes of grain per hectare under well-watered conditions; this could result in a 50 percent increase in average farm yields to about 13 tonnes/ha by 2050.

Rice: Mitchell, Sheehy and Woodward (1998) predicted that conventional selection could result in a tropical and subtropical rice PY of 11.3 tonnes/ha for IR72 maturity. On the other hand, application of IRRI's New Plant Type principles in the large Chinese "super rice" breeding programme has already given a 10 to

20 percent jump in PY, to 12 tonnes/ha, in hybrids grown in lowland eastern China (Peng *et al.*, 2008). Sheehy *et al.* (2007) predict yields of 50 percent greater than the present 9 tonnes/ha if C_4 photosynthesis could be engineered into rice; the relative advantage could rise as global temperatures increase.

Maize: It is difficult to find consistent PY projections for maize. Chile has the world's highest national maize yield (11.5 tonnes/ha from 130 000 ha in 2005 to 2007) and yields of more than 20 tonnes/ha have been observed under irrigation in Chile's central valley (unpublished data), but this may reflect the more favourable climate compared with that in the United States Corn Belt. This is obviously an issue of great interest in the mid-west of the United States, given the huge maize research investments there. On the one hand, Cassman *et al.* (2003) argue that the limit of PY has already been reached under irrigation in Nebraska, as reflected in a stable average yield of contest winners of 18.8 tonnes/ha. Higher yields have been observed in contests since 1975 (of 21 to 23 tonnes/ha)[14] but the Nebraska number is an average for the period 1983 to 2002. At the other extreme, Monsanto, a leading seed company,[15] has set a goal of doubling United States maize FY by 2030, based on 2000 yields of 8.5 tonnes/ha, resulting in a FY target of 17 tonnes/ha (Edgerton, 2009). This would be unprecedented breeding progress (2.3 percent exponential, or 3.3 percent linear at the outset, 1.7 percent by 2030); but can it be sustained over time, and what would it imply for PY increase to 2030? United States yields for 2007/2009 averaged 9.82 tonnes/ha, with a 2 percent increase per year from 2000 to 2008, already well behind the goal. Monsanto breeders claim they will achieve these record gains in equal measure through conventional breeding, molecular-aided marker selection and genetic engineering for yield. FY in Iowa is about 12 percent above the United States average FY for maize, so Monsanto's claim translates into an Iowa FY of about 19 tonnes/ha in 2030. The PY – FY yield gap in Iowa is currently thought to be about 45 percent (Table 10.4). If this gap is sustained, it would imply a PY of 27 tonnes/ha across Iowa by 2030, somewhat higher than the theoretical maximum yield of 25 tonnes/ha cited by Tollenaar and Lee (2011). Of course the yield gap could close further, but even at 25 percent, PY would be 24 tonnes/ha. A further complication for these projections are the recent findings by Hammer *et al.* (2009), which imply that yield and water use are more tightly coupled than previously believed and that there may not be enough water from rainfall to support much higher yields in Iowa, a region usually considered to be relatively free of water stress and operating under PY not PY_W.

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14. The highest yield reported in the United States National Corn Growers' Association yield contests in 2007 was 23.9 tonnes/ha: www.ncga.com/files/pdf/2008cycnationalwinners.pdf. Contest yields (rainfed) in Iowa and Nebraska also show steady yield progress at levels about double the state averages.

15. www.monsanto.mediaroom.com.

Water-limited potential yield

Equation (3) underlies understanding of PY_W progress, despite it limitations (Blum, 2009). There has been breeding progress for PY_W, but generally at lower absolute and even relative rates than that for PY. Initially, progress has derived from better fitting of the crops' phenological development to the particular rainfed environments, usually meaning selection for earliness – whether for wheat in a Mediterranean environment or maize in a tropical one. This brings the growth of the crop into a moister period, when TE is higher[16] and reduces the risk of exhausting available moisture before grain filling (maintaining HI). PY_W progress has also derived from spill-over of progress in PY; for example, when higher intrinsic HI is maintained under stress, yield improves in both equations (1) and (3), and higher RUE may also deliver higher TE. Recent analysis of old versus new maize hybrids shows that progress in a dry year in Iowa matches that under wetter conditions (Duvick and Cassman, 1999), although the authors claim that this is spill-over of improved micro-stress tolerance with higher PY, not spill-over of PY *per se*. Such is the importance of variation in flowering date and PY that attempts to study other factors in PY_W variation usually correct for them (Fischer and Maurer, 1978; Bidinger, Mahalakshmi and Rao, 1987), but the picture is less clear for rice, with marked specific adaptation to flooded or rainfed conditions limiting spill-over from favourable environments.

Numerous other factors may influence performance under rainfed conditions, including early vigour, to cover the soil and enhance T at the expense of soil evaporation (a special advantage of proper soil nutrition under rainfed conditions); osmotic adjustment; leaves with waxiness and low epidermal water conductance; and deeper roots (Blum, 2009). For example, for maize in Iowa, it has been suggested that selection has increased tolerance to stress at flowering (Campos *et al.*, 2004) and significantly increased deep-soil water uptake (Hammer *et al.*, 2009). Modest gains in PY_W of wheat have also been made by selecting for TE directly (Richards, 2004). However, many putative drought tolerance traits have not proved useful as selection criteria, or carry a significant yield penalty under well-watered conditions.

One area of opportunity derives from cereals – especially rice and maize – being sensitive to drought at flowering, when a sharp reduction in the numbers of kernels set can occur (Fischer, 1973; 1985; Bruce, Edmeades and Barker, 2001), inevitably reducing HI. Maize ovaries starved for carbohydrate grow slowly, and the ovary's ability to be successfully fertilized can be severely reduced.

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[16] TE is inversely related to the prevailing vapour pressure deficit (vpd) of the air.

Pollen is also directly affected by water stress at meiosis in rice and wheat, and carbohydrate starvation does not explain all of the damage. Selection gains occur when stress is managed to coincide with these critical periods. Indirect selection for rapid ear growth rates in maize under managed drought stress has resulted in improved tolerance (Edmeades *et al.*, 2000). Useful genetic variation (not genetically modified) in the sensitivity of grain set in wheat to water stress around meiosis has recently been demonstrated (Ji *et al.*, 2010).

Water-limited potential yield projections

A variation of equation (3) used in Australia (French and Schultz, 1984) states that $PY_W = k\ (ET – 110)$, where ET is water used in mm, and 110 mm estimated soil evaporation, while k = 20 kg/ha/mm is essentially an average TE across the season multiplied by a good value for HI. This defines an upper limit to PY_W of wheat for a given level of ET; for example if average ET for wheat in southern Australia is 300 mm[3], PY_W is 3 800 kg or 3.8 tonnes/ha (c.f., current national average is about 2 tonnes/ha). This approach is an oversimplification, but has proved a very useful practical guide to PY_W in Australia (Fischer, 2009) and for discussing PY_w increase (Passioura and Angus, 2010). Yield increase through breeding or agronomy can only come from increases in T (e.g., by storing more water, developing a more efficient root system or reducing losses through evaporation from soil or by weeds), or from increases in TE or HI. These generally appear to be modest in extent, but added together may lift PY_W by 25 percent (Passioura, 2002; Passioura and Angus, 2010).

Revisiting equation (3), the largest differences in TE are seen between C_4 and C_3 crops, which average 159 and 83 g of biomass per kilogram of water transpired, respectively (Loomis and Connor, 1992). In a warmer and water-limited world, this provides another strategic reason for developing C_4 versions of rice, wheat and other crops, although C_4 crops are not necessarily more drought-tolerant than C_3 ones (Ghannoum, 2009). There is probably continued scope for PY_W increase through increasing HI, particularly via lessening water shortage-induced reductions in grain number. There is no sign of slowing in recent striking PY_W progress of about 100 kg/ha (or 5 to 8 percent) per year that has been achieved under managed drought stress in the field in tropical maize over a ten-year period, mainly through increases in HI. This selection methodology is also currently delivering useful gains in farmers' fields in Africa (Bänziger *et al.*, 2006). Progress for drought tolerance in rice is also encouraging, with a single large-effect chromosomal region adding 47 percent to yield under severe drought (Bernier *et al.*, 2007), and pedigree selection under managed stress reporting gains of 4 to 10 percent per year (Venuprasad *et al.*, 2008). Genetic engineering possibilities abound in the literature and are discussed in a later subsection.

Exploiting heterosis

Heterosis, present in hybrids and obtained by crossing two genetically dissimilar parents, is considered a form of stress tolerance, and is often greater for PY_W than for PY. In general, hybrids offer about 15 percent yield advantage over open-pollinated parents in maize, and about 10 percent over inbred parents in wheat and rice (e.g., Bueno and Lafarge, 2009). Hybrids have been widely used in maize for 80 years, and are deployed on about 70 percent of the global cultivated area. In rice and wheat, both normally self-pollinated crops, the limitation is the poor yield of the female parent line when it is forced to out-cross, resulting in expensive seed production. Adoption of hybrids in rice is still quite low, except in China where indica hybrids account for 60 percent of the planted area. In wheat, technical issues in seed production have prevented any large-scale adoption. Seed yield constraint is likely to be resolved in the next ten to 20 years, probably using genetic modification technology, thus permitting hybrids to take over most of the world's rice and wheat area. CIMMYT is not optimist about wheat hybrids (Dixon, Braun and Crouch, 2008), but recently it has launched a new hybrid wheat project, while at IRRI there is now strong confidence regarding the viability of indica hybrids for tropical latitudes. Thus wheat, rice and maize yields could rise in one-off yield increases of 10, 8 and 5 percent, respectively, as the proportion of hybrids under cultivation approaches 100 percent. Because there is an on-farm advantage to growing fresh F1 hybrid seed every year, hybrids foster a viable commercial seed industry and a superior level of intellectual property (IP) protection, thereby creating a positive environment for private investment in crop improvement.

Genetic modification using transgenes

Prospects for augmenting PY by increasing P_{max} and RUE through genetic modification are currently based mainly on engineering C_4 photosynthesis into rice, and possibly wheat, or on modifying Rubisco and Rubisco activase enzymes or other enzymes close to Rubisco. These are formidable technical challenges. Other promising genetic modification routes to higher PY have been proposed, but few have been demonstrated in the field, and the compensatory response among yield components is often overlooked. Engineering better abiotic stress resistance (greater PY_W) may be easier, although many putative drought tolerance genes reduce yield unacceptably in well-watered conditions, or simply fail to deliver in the field. In 2012, Monsanto aims to launch commercial maize hybrids carrying the cold shock protein gene *cspA* from *Bacillus subtilis*, which functions under drought stress as a protein that protects RNA from degradation and for which there are some credible published field plot data (Castiglioni *et al.*, 2008).[17] Reports suggest that this transgene is active throughout the life of the maize crop, rather than affecting stress tolerance only at flowering, and will lift yields by 6 to 10 percent under a moisture stress that reduces yields to about 50 percent of irrigated yield levels.[18] This may mark a breakthrough for genetic modification breeding targeting abiotic stress and crop yield. Of particular interest is Monsanto's intention to release this technology for use in adapted maize in sub-Saharan Africa on a royalty-free basis, through the Water Efficient Maize for Africa Project, in an exciting private-public sharing of cutting-edge technology to benefit those who need it most. Preliminary results in Southern Africa suggest the gene is very background-specific, meaning that it has little or no effect in some conversions, and has its greatest effect around flowering. Several other recent studies point to possibilities of greater stress tolerance in rice, which is the common candidate crop for published work on genetic modification for PY because the genome is sequenced and widely available. However, there are few convincing published reports of yield effects due to transgenes in either wheat or rice (but see Xiao *et al.*, 2009).

Engineering for biotic stress and herbicide resistance has already been hugely successful. It has had a significant environmental benefit through reduced pesticide applications, and has lifted yields of crops under insect attack (Brookes and Barfoot, 2009), but has had little effect on PY *per se*. Engineered herbicide tolerance in soybeans, maize and canola has facilitated conservation tillage and permitted more timely planting, with modest benefits for yield. Transgenic resistance to corn root worm in maize has improved yield under water-limited conditions where the insect infestation is severe by retaining more roots and increasing water uptake; before genetic modification it was very difficult to control this pest. The benefits of genetic modification for maize yield are probably reflected by the rate of increase in maize yields in Iowa, which have been significantly greater than those in France and Italy since 1996, the year transgenic maize was first introduced to farmers' fields (Figure 10.13). Transgenic technologies are not used in the field in France and Italy, but an estimated 90 percent of Iowa maize carries at least one transgene for herbicide or insect resistance. It is unlikely that less favourable weather in Europe than in Iowa accounts for all of this difference.

In conclusion, further yield increase via genetic modification for biotic stress resistance and herbicide tolerance is a good possibility; this yield gap is closing. Whether increase will also come from increased PY and PY_W *per se* is less

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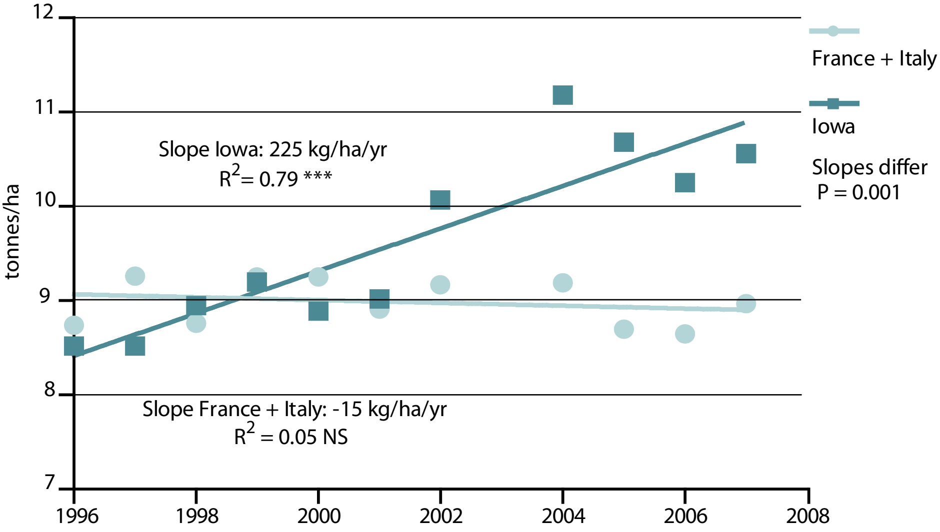
[17] An earlier genetically modified maize from Monsanto incorporating an *Arabidopsis* transcription factor and showing improved field drought tolerance (Nelson *et al.*, 2007) appears to have been allowed to lag.

[18] www.monsanto.com.

certain. However, the likelihood of transgenic options for stable and long-lasting disease resistance in rice and wheat in the next 15 years or so has the advantage of sharply reducing the need for maintenance breeding in these two crops, an activity that currently consumes about 30 to 50 percent of the breeding effort at IRRI and in the CIMMYT Wheat Program – a much larger proportion than in maize. This would release considerable additional breeding resources for focusing on PY in rice and wheat.

Figure 10.13
Maize yields in Iowa and in France and Italy



2003 is excluded because of severe drought in Europe.
Sources: USDA and FAOSTAT, 2009.

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 the demand for grains over the past century. It has depended on large investments in empirical yield testing, and has 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 percentage of current yield and in absolute terms, has been declining over the past decades for rice and wheat (see section on Sources of yield gains in the breadbaskets), but apparently not for maize, although gain per unit of investment has probably been declining for some time in maize too (Duvick and Cassman, 1999).

Molecular breeding technologies offer real hope of accelerated progress, provided useful genetic variation continues to be available. These technologies, such as marker-assisted selection (MAS) and marker-assisted recurrent selection (MARS), are now being integrated with conventional breeding approaches, but have not been widely adopted outside industry leaders in the private sector because of capital constraints. As noted previously, Monsanto has set a goal of doubling maize yields between 2000 and 2030, claiming accelerated gains in yield (2.5 times their historical rates) partly via more efficient MAS.

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[19] suggest that gains in yield in elite germplasm of 4 percent per year are possible (Crosbie *et al.*, 2006) in favourable and stressed environments, effectively doubling the rate of yield gain compared with conventional breeding (Eathington *et al.*, 2007; Edgerton, 2009). Association mapping is based on dense marker maps, usually using single nucleotide polymorphisms, a full-genome marker scan, accurate yield assessment, and statistical algorithms that develop many gene-to-phenotype associations (Heffner, Sorrells and Jannick, 2009). Again, the biggest unknown is how useful transgenic variation will be in creating novel variation to supplement natural variation for grain yield traits, such as RUE and 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 PY. The same applies to rainfed wheat at intermediate latitudes, where frost resistance at flowering would likely bring earlier flowering and significant yield benefits. These additional genetic modification gains appear technically feasible, but far less certain.

Realizing these additional gains requires that genetic variation (natural or transgenic) is present and that genotypic (laboratory assays of genes and markers) and phenotypic data (field measures of plant performance) can be brought together in the tight time frame demanded by large breeding programmes today. Physiological understanding will be critical to yield increase via genetic modification, but maybe less so for MAS, MARS and genomic selection, which 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-

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[19] This is now more commonly referred to as "whole of genome selection" or "genomic selection".

you-go" (Podlich, Winkler and Cooper, 2004), deliver on their early promise. Phenotyping capability in the field and greenhouse is expanding far more slowly than the ability to genotype huge arrays of germplasm in the laboratory, and cost per phenotypic data point is declining far more slowly that cost per genotypic data point, but both classes of data are critical to future success in crop improvement. Improvements in phenotyping efficiency will depend largely on a combination of carefully managed stress levels in the field, and remote sensing of large numbers of plants, again with a greater role for physiology than in the past. Such changes will likely require significant advances in agronomy, especially in N nutrition, if they are to be fully exploited in the farmer's field.

Intellectual property (IP) considerations are a constraint to the widespread use of molecular breeding techniques, but offer the protection that ensures continued private sector investment. Coupled with the use of hybrids, IP protection where farmers and companies benefit from annual purchase of seeds provides a powerful incentive for investment in crop improvement, as is 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 programmes of CGIAR centres such as CIMMYT and IRRI and currently in the global operations of multinationals such as Monsanto, Dupont, Syngenta and Bayer. Among small and medium enterprises (SMEs), CGIAR centres and multinational seed companies, research alliances for addressing the needs of national or niche markets have generated viable business models for seed SMEs, and are needed to maintain a healthy competitive environment in the seed industry.

Transformation and marker-aided back-crossing are now relatively cheap and routine. However, the search for appropriate candidate transgenes, IP agreements and royalties, regulatory compliance and commercialization is an expensive undertaking, perhaps costing USD 50 to 70 million per gene in industrial countries. The scale of these costs excludes many developing countries and SMEs from the technology, and the recent agreements to waive IP restrictions on the use of technologies associated with high pro-vitamin A "Golden Rice" and the Water Efficient Maize for Africa Project are welcome signs of corporate social responsibility and public-private collaboration. However, regulatory compliance costs remain high, and have increased greatly in recent years. This reflects societal unease with genetic modification technology, which should reduce in time as experience reveals the true level of risk. In the meantime, with very few exceptions, unease has prevented the 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 the PY and yield stability of staple food crops.

Yield potential toward 2050

Prophecy is an uncertain business, and can only be based on extrapolation of existing trends. An accelerated and sustained gain in cereal yield progress on the farm is needed, with an increase from less than 1 percent to about 1.5 percent per annum: this will come largely from new varieties with increased PY, helped by the development of agronomic practices that exploit the new capability while conserving agriculture's natural resource base. New varieties will also need to be able to cope with climate change. The following areas call for increased research investment:

- 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, remote sensing, informatics and biometrics are critical tools in this.
- 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. Because crop plants have a 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 out-crossing barriers for successful hybrid production in rice and wheat.
- Crop genetic enhancement, through the use of wild species (for wheat, see Ortiz *et al.*, 2008).
- Ongoing focus on stress tolerance as well as PY in all crops. This will continue the trend towards higher yields, enhanced yield stability and improved input use efficiency that is already evident in the temperate maize crop.
- Continued strong investment in protecting genetic and agronomic gains through pest resistance, because climate change will bring changes in the pest-predator balance. The global soil resource must also be protected

from erosion, which is a huge unfulfilled role for conservation tillage, and from degradation caused by nutrient depletion, providing an inescapable role for efficient use of chemical fertilizers.

A suitable *policy framework* is needed to attract private investment, develop technology and guide its benefits to those most in need. Such a framework should include:

- 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, which will greatly increase the range of tools at the breeder's disposal;
- development of a win-win social contract for sharing technology outcomes with resource-poor countries and encouraging more private-public partnerships in the developing world; both private and public sectors are key components of efficient international agricultural research, and strengthening of the CGIAR system and of regional and global commercial activities are essential complements.

Prices, efficiency, productivity and R&D investment

The ultimate concern is not with yields *per se*, but with improving productivity and reducing the prices of food staples. Declining real prices of food staples for 1961 to 2006 – by annual average rates of 1.8 percent for wheat, 2.6 percent for rice and 2.2 percent for maize in world markets – have been a major source of poverty reduction, given that food staples account for a large share of expenditures of the world's poor (for a review of the evidence, see World Bank, 2007). This decline in real prices has been driven by growth in TFP, averaging 1.0 percent globally for all agriculture for the period 1961 to 2006, and 1.7 percent for the industrial countries that provide most grain exports (Fuglie, 2008). A distinguishing feature of this period has been that TFP has risen faster than prices have declined, so both farmers and consumers have benefited (Lipton, 2005).

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

Prices of non-renewables

Looking ahead 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 the manufacture of nitrogenous fertilizers and the provision of farm power, and reserves of phosphates as an essential macroelement for soil fertility.

Fossil fuels: All indications are that fossil fuels have entered a new era of higher and more volatile prices, with an expected upwards trend. Modern agriculture uses an estimated 12.8 EJ[20] of fossil energy, or about 3.6 percent of global fossil fuel consumption. This is roughly divided as 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 to 0.16 GJ[21] per tonne of grain for rice in the Philippines and maize in Mexico in traditional systems, to 2.4 GJ/tonne for improved rice in the Philippines, 2.5 GJ/tonne for wheat in Germany, and 5.9 GJ/tonne for irrigated maize in the United States of America (FAO, 2000; Langreid, Bockme and Kaarstad, 2004). Both machinery and fertilizer costs account for growing shares of production costs in developing countries (World Bank, 2007).

Nitrogen: Current global consumption of around 100 million tonnes of N fertilizer provides more than two-thirds of the N taken up by crops (Socolow, 1999). Although N fertilizer use is now steady or falling in industrial countries, it continues to rise in developing ones (see the section on Setting the scene). Future projections of N fertilizer consumption vary widely, from a relatively modest increase to 121 million tonnes in 2050 (Wood, Henao and Rosegrant, 2004) to 180 million tonnes in 2070 (Frink, Waggoner and Ausubel, 1999), depending on assumptions, including N use efficiency change.

Fossil energy (usually natural gas) accounts for 70 to 80 percent of the cost of manufacturing N fertilizer.[22] Increased efficiency in manufacturing allowed N fertilizer prices to fall until the 1980s. For example, the energy for manufacturing ammonia using the best technology at the time declined from 80 GJ per tonne of ammonia in 1950, to 50 GJ/tonne in 1980, and about 40 GJ/tonne in 2000 (Smil,

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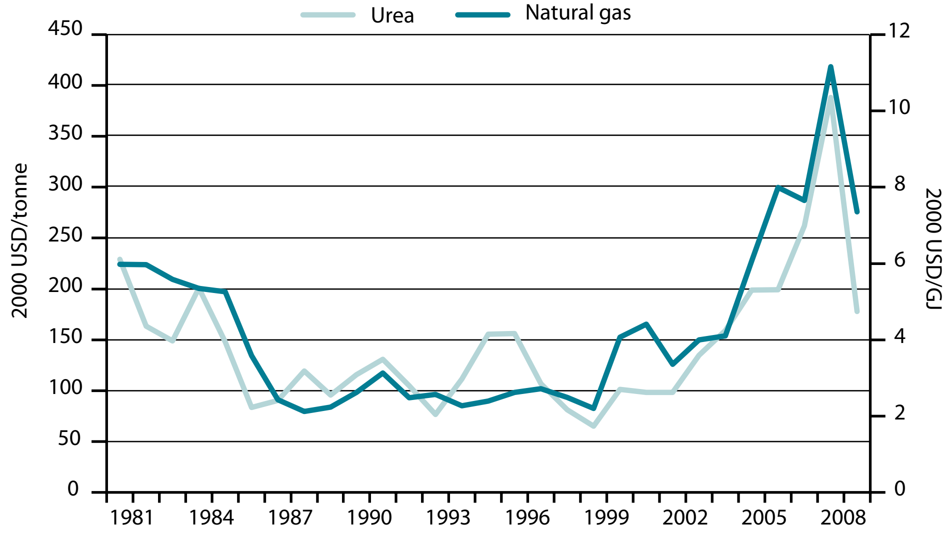
[20] 1 EJ = 10^{18} joules.

[21] 1 GJ = 10^{9} joules; 1 litre of diesel contains 38 MJ of energy, 1 tonne of maize or wheat about 15 GJ.

[22] The actual figure varies depending on the location and age of the manufacturing plant, the fertilizer product, and the costs of natural gas. Although natural gas is cheap in the Gulf States, fertilizer must still be transported to the point of consumption (A. Roy, personal communication).

2008).[23] However, the best plants are now approaching the stoichiometric limit for energy efficiency. Since 1981, N prices have closely tracked energy prices, with 1 tonne of urea (46 percent N) costing about 40 times as much as 1 GJ of natural gas (Figure 10.14), although significant efficiency gains could still be made by abandoning older less efficient plants.

Figure 10.14
Real prices of urea in bulk in Eastern Europe (left axis), and natural gas in Europe (right axis)



Source: World Bank data files.

As the major efficiency gains have already been made, it is likely that the price of N fertilizer will rise in line with energy prices. In addition, some high-income countries are now taxing N fertilizer use, as a disincentive to pollution. A tax on greenhouse gas emissions is also likely in the future. This would hit prices of N fertilizer particularly hard, owing to N fertilizer's fossil energy intensity and the fact that once applied it can become a significant source of nitrous oxide, an especially potent greenhouse 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

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[23] The conversion of ammonia to urea adds 10 GJ per tonne of N to the energy costs of fertilizer, giving a final energy cost of urea of 55 to 58 GJ per tonne of N (Smil, 2008).

studies have documented low on-farm efficiency of applied N, with an average of only 33 percent being taken up by the crop, dropping to 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, in many cases, lower application rates, N use efficiency could be improved by 33 percent for irrigated maize to more than 100 percent for rainfed rice (Balasubramanian *et al.*, 2004) (Table 10.7). Improvement is already evident in United States maize, for example, where N use per hectare has declined through more site-specific application rates, even as yields have increased (see the section on Sources of yield gains in the breadbaskets). Precision agriculture provides new tools for improving efficiency further (discussed in the following subsection). New products such as controlled and slow-release fertilizer can also increase efficiency with rice (IFDC, 2009). In Bangladesh, more than half a million farmers have adopted Urea Super Granules, which are deep-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). As plant breeding raises yields, it inevitably results in more efficient N use (Ortiz-Monasterio *et al.*, 1997; Bänziger, Edmeades and Lafitte, 1999; Echarte, Rothstein and Tollenaar, 2008); this general principle also applies to most other inputs, such as phosphorus and water (de Wit, 1992; Fischer, 2009).

Table 10.7
Mean recovery efficiency of N (REN) for harvest crops under current farming practices and research plots

	Mean REN under current farming practice	Mean REN in research plots	Maximum REN of research plots
Crop	*(% of N applied)*		
Rice			
Irrigated	31–36 (Asia)	46–49	88
Rainfed	20	45	55
Wheat			
Irrigated	33–34 (India)	45–57	96
Rainfed	17 (USA)	25	65
Maize			
Irrigated and rainfed	36–57	42–65	88

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

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. Legumes cover only about 11 percent of cropped land; although using generally lower-yielding legumes to replace more cereals would depress world food supplies, there are some opportunities for fitting legumes into gaps in even relatively intensive cropping systems, as shown by the adoption of 60-day mung beans on nearly 1 million ha in the rice-wheat system of the Indo-Gangetic plains, which 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 is unlikely to be a feasible technology by 2050, and the gain in N would have to be balanced against a possible yield penalty for energy diverted to N fixation (Ladha and Reddy, 2000).

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 to 75 percent, as well as helping to sequester soil carbon. Globally, no-tillage is now used on an estimated 100 million ha of about 1 170 million ha of total cropped land (FAO, 2008b), 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 10.8). There are also good examples from irrigated South Asian systems, where small-scale farmers have adopted zero tillage on as much as 5 million ha of wheat in rice-wheat systems, with estimated savings in fuel costs of 60 to 90 percent and an increase in wheat yields of 11 percent (Erenstein *et al.*, 2008; FAO, 2008a).[24] Conservation tillage has also been suggested as a potentially important source of carbon sequestration in tropical soils (IPCC, 2007).

Table 10.8
Estimated area under no-tillage[a] in major adopting countries

Country	1988–1991 *(million ha)*	2003–2007 *(million ha)*	2003–2007 *(%)*
Argentina	0.5	19.7	67
Brazil	1.4	25.5	38
Paraguay		2.1	49
Canada	2.0	13.5	26
USA	6.8	25.3	14
Kazakhstan		1.8	8
Australia	0.4	9.0	36
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 of sufficient width and depth to obtain proper seed coverage only. No other soil tillage is done (FAO, 2008a).

[b] Including countries with less than 1 million ha in 2003 to 2007.

Source: FAO, 2008b.

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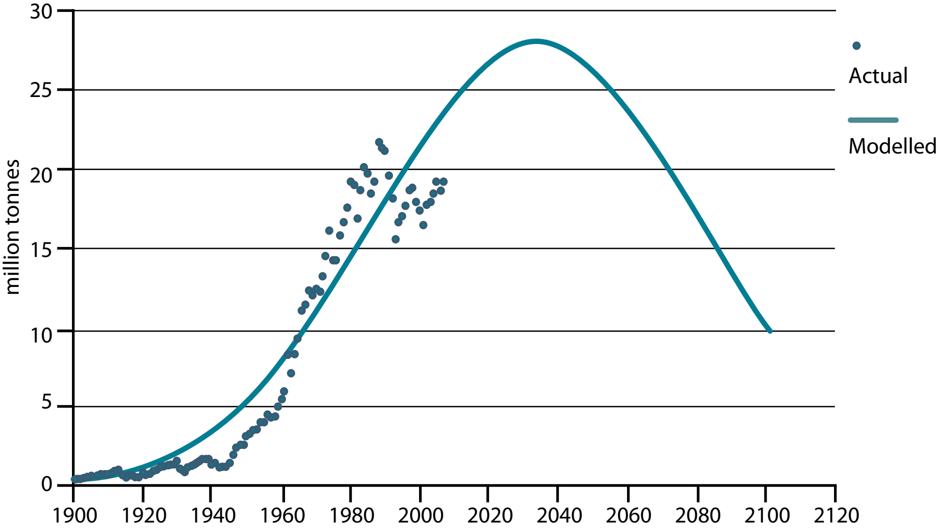
[24] This figure is not included in Table 10.8 because farmers practise tillage in the following rice crop, so do not meet the strict definition of zero tillage.

With less than 10 percent of the world's cropland under conservation tillage, wider adoption of the practice represents a major opportunity for improving the sustainability, energy efficiency and yield of cropping. However, 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. If successful, current discussion of payments for soil carbon sequestration will greatly add to the incentive for adopting conservation tillage, provided conservation tillage sequesters more C in soils – an issue that is currently under much scrutiny – and monitoring systems can be devised.

Phosphorus: Phosphorus (P) is the other major non-renewable resource for which scarcity could significantly affect crop yields by 2050. Recent work by Cordell, Drangert and White (2009) estimates that production of phosphates will peak by 2034, using the Hubbert curve that predicts declining production of oil and other mineral resources when half of reserves have been exploited (Figure 10.15). Production will also become more concentrated, especially in Morocco, as the United States of America has only 20 to 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. A recent report (IFDC, 2009), however, casts considerable doubt on the imminent P scarcity predicted by Cordell, Drangert and White (2009), estimating the global supply of phosphate rock reserves of reasonable grade to be several hundred times annual consumption.

As with N, there is much room for enhancing the efficiency of P use. Of the 14.9 million tonnes of P mined for agriculture, only 6.1 million tonnes 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, although the big difference 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 that 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 P prices rise (Cordell, Drangert and White, 2009).

Figure 10.15
Projection of peak global phosphorus extraction



Source: Cordell, Drangert and White, 2009.

Agricultural price policies

Price policies can also be important in achieving high yields and efficiency. Historically, developing countries have taxed their agriculture sectors heavily, in part to provide cheap food, penalizing overall growth rates in the sector. This situation has largely been resolved under the 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. 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 programmes have favoured a few crops and discriminated against the adoption of more sustainable cropping systems, especially crop rotations.

Subsidies on many inputs, and outmoded pricing structures, especially for 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 the current high levels of input use, they undermine incentives to use inputs more efficiently. Supporting institutional reforms will also be important, such as 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 the adoption of fertilizers and stimulate the development of input markets. Several countries have reintroduced such subsidies (World Bank, 2007), but high fiscal costs and the displacement of commercial sales threaten their long-run sustainability and effectiveness.

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 in Western Europe and a low of 70 percent in Eastern Europe (Bravo-Ureta *et al.*, 2007).

While most of these studies fail to account adequately 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 in what is often termed "precision agriculture" have much potential to enhance productivity, as well as contributing to more sustainable production systems. These new tools include yield mapping, leaf testing to time N application, remote sensing, crop modelling and expert systems, improved weather forecasting and wireless in-field monitoring; they aim to improve input use efficiency by allowing inputs to be calibrated more precisely to within-field variability and seasonal conditions (Sudduth, 2007). They are also being applied in small farm agriculture; for example, very small-scale farmers are using the leaf colour chart to time N application on rice (Islam, Bagchi and Hossain, 2007). With the spread of mobile phones and village information kiosks, farmers can increasingly tap external sources of information on prices and crop management, and identify pests and diseases remotely.

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

Box 10.2 - Is TFP growth slowing?

Recent work by Fuglie (2008) provides an up-to-date and comprehensive overview of TFP growth (see following table). While these estimates are for all agriculture and not just cereals, the general conclusion is that TFP growth has accelerated in the most recent period since the green revolution, 1991 to 2006, in spite of slower output growth. Input growth has slowed in all regions, and in developed countries is now negative, especially in the former Soviet Union, 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 cancelled slower growth in cereals. High growth in both output and TFP is led by large countries, especially Brazil and China, with TFP growth of more than 3 percent per year. Nonetheless, Fuglie (2008) recognizes that cereal growth has slowed significantly and that TFP growth for individual commodity groups may show diverse patterns. A recent review by Kumar, Mittal and Hossain (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, Ali and Byerlee, 2001).

In developing countries overall, the share of growth accounted for by TFP has risen from one-third in the period 1970 to 1990 to nearly two-thirds in 1991 to 2006. In line with the earlier analysis, sub-Saharan Africa is the outlier, with growth dependent on land expansion rather than TFP – 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).

Growth of total output, input and TFP in agriculture

	Output *(%/year)*		Input *(%/year)*		TFP *(%/year)*	
Region	1970–1990	1991–2006	1970–1990	1991–2006	1970–1990	1991–2006
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
Near East and North Africa	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
Russian Federation, Ukraine and Central Asia	0.99	-1.57	1.17	-3.95	-0.17	2.38
Developed	1.35	0.87	-0.27	-1.18	1.61	2.05
Transitional[a]	0.95	-1.48	0.94	-3.28	0.00	1.79
Developing	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, personal communication, recalculated from Fuglie, 2008.

Prospects for TFP growth

What does all of this mean for TFP growth? In general, the share of TFP growth in agricultural output growth grows as agricultural economies develop (Pingali and Heisey, 1999). TFP growth was responsible for half of output growth after 1960 in China and India, and for 30 to 40 percent of the increased output in Indonesia and Thailand (World Bank, 2007). There is little evidence that growth in TFP is slowing (Box 10.2).

TFP growth is largely explained by investments in research, extension, education, irrigation and roads, and by policy and institutional changes (Pingali and Heisey, 1999; Binswanger, 1989; World Bank, 2007; Kumar, Mittal and Hossain, 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 TFP gains in Pakistan and China in the post-green revolution period (Rozelle *et al*., 2003; Ali and Byerlee, 2002). Even in sub-Saharan Africa, the impact of R&D has been identified as important in the region's (limited) productivity growth (Lusigi and Thirtle, 1997).

The key role of R&D investments

Considerable uncertainty surrounds the question regarding what level of investment in R&D will be needed to realize the gains in yields and productivity necessary to secure global food security to 2050. For example, IFPRI's high R&D investment scenario reverses an upwards trend in real prices of grain to 2050 relative to the baseline, and boosts yield growth from 1.0 to 1.4 percent (see subsection on Scenarios to 2050 and the future yield challenge) and involves an approximate doubling of agricultural R&D, along with increases in other key areas of agriculture (Hubert *et al*., 2010). Von Braun *et al.* (2008) estimate that a doubling of investment in R&D in developing countries would increase R&D's contribution to overall output growth by 1.1 percentage points (i.e., an approximate doubling of current rates), sufficient to ensure a continued decline in poverty (and presumably food prices) through 2020. However, there remains a wide margin of uncertainty in estimates of the quantitative relationship between R&D investments and yield and productivity growth, especially regarding 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 are likely to increase their dependence on food imports. Spill-overs from R&D in industrial countries are also important for 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, and a 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 puts private sector spending on maize research in the United States of America at about USD 1 billion a year, compared with USD 181 million in 1990 (in 2008 dollars) (Byerlee and Lopez-Pereira, 1994). This huge increase is a likely explanation for the continuing impressive yield gains in maize in the United States, and in similar 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 on investment in R&D down from their very high levels of more than 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 rice. Unpublished data from USDA indicate a levelling of private spending in the United States of America since 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.

It is likely that over the long term, productivity-enhancing investments will be 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.

Conclusions

It is common that when world grain prices spike, as they did in 2008, a small enclave of world food watchers raises the Malthusian spectre of a world running out of food. The original demon of an exploding population has evolved to include the livestock revolution and, most recently, biofuels. However, since the 1960s, the global application of science to food production has maintained a strong track record of staying ahead of growing demands. Even so, looking to 2050 new demons on the supply side, such as water and land scarcity and climate change, provoke claims that “this time it is different”. Even so, after reviewing what is happening in the breadbaskets of the world and what is in the technology pipeline, there is cause for cautious optimism about the world’s ability to feed itself to 2050; this optimism was shared by Evans (1998) at the end of his long excursion through these same issues.

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 developing countries, and nowhere more so than in sub-Saharan Africa, where food supply is the most precarious.

Second, in the short to medium term, many of the newer technologies that are in their early stages of adoption promise a win-win combination of enhancing productivity and managing natural resources sustainably. These include conservation farming approaches based on no-tillage and the genetic modification technology revolution – both still used on less than 10 percent of the world’s cropland – and information and communication technologies for more efficient and precise management of modern inputs, which are still at an even earlier adoption phase.

Third, yield gains are not achieved by technology alone, but also require complementary changes in policies and institutions. This is now recognized in much of the developing world, and policies are becoming more favourable to rapid productivity growth, while a range of innovations in risk management, market development, rural finance, farmers’ organizations and the provision of advisory services show considerable promise for making markets work better and providing a conducive environment for technology adoption. In sub-Saharan Africa, these innovations are a necessary condition for wider adoption of critical technologies such as fertilizer. The recent progress in cereal yields in Egypt reflects attention to technology, policy and institutions together.

Fourth, plant breeders continue to make steady gains in PY and PY_W, 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 from conventional breeding is becoming more difficult. Genomics and molecular techniques are now being regularly applied to speed breeding in the leading multinational seed companies and elsewhere, and their costs are falling rapidly. Transgenic (genetic modification) technology has a proven record of more than a decade of safe and environmentally sound use, and its potential to address critical biotic and abiotic stresses in the developing world – with positive consequences for closing the yield gap – has yet to be tapped. The next seven to ten years are likely to see its application to major food crops in Asia and Africa, and after its initial adoption, the currently high regulatory costs will begin to fall. However, this will require significant additional investment, not least in the areas of phenotyping on a large scale, and it still takes ten to 15 years from the initial investment before the resulting technologies begin to have major impacts on food supply. Transgenics for greater PY_W may also appear by then, but trangenics for greater PY arising from significant improvements in photosynthesis may take longer than even the 2050 horizon.

These are broad generalizations, and there are important variations 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, industrial quality constraints on breeding, and the greater role of water stress in wheat's production environment. Yield gains in rice are more problematic, but demand growth is also lower for rice, although it is a particularly important food staple for the poor of Asia (where rice area is shrinking) and increasingly of Africa. 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 agriculture sector in the past decade.

However, a number of cautions should be raised. First, this chapter has 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, such as cassava in Africa. Others are commercial crops for an urbanizing population – potatoes for fast foods, and oilseeds for oil and feed.

Second, the future of biofuels is the new wild card in the world food economy. To some extent the need to accelerate global cereal yield trends beyond the historic annual rate of 43 kg/ha for 1961 to 2007 relates to this new demand. By 2020, the industrial world could consume as much grain per capita in its vehicles as the developing world currently consumes per capita directly for food.

Third, many countries face huge challenges in achieving food security, even from the narrow perspective of food supply. There is less cause for concern about China and India, as they should continue to be largely self-sufficient for food needs (although dependent on imports for part of their feed needs), but much depends on investments in R&D and management of natural resources. However, many other countries do not have the capacity to import large amounts of grain, or find it prohibitively costly to do so, but still have very high population growth. Most of these countries are in Africa, but even Pakistan, with an estimated 335 million 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 towards adaptation rather than yield improvement – adding a new dimension to maintenance research.

Past agricultural success has been achieved partly by mining non-renewable resources, such as fossil energy, phosphate and underground water. This chapter's review of the impact of looming limitations for this strategy raises major concerns, and places a premium on improved efficiency in using these resources, which must be at the top of the agenda for feeding the world in 2050. Contrary to popular opinion, however, generally increased yield through breeding and modern agronomy is lifting resource use efficiency.

The history of agriculture in the twentieth century teaches that investment in R&D will be the most important determinant of whether this chapter's optimistic view is realized. There are indications that major developing countries such as China, India and Brazil are poised to close their gaps in research intensity with the industrial countries. CGIAR is also revamping its efforts, aiming to double its budget in the coming years. However, many technological orphans are falling behind in R&D spending (Chapter 9 in this volume). The private sector must also be encouraged to make a major impact beyond its mainstays of maize and soybeans, especially in rice. Innovative partnerships will be needed to ensure access to and adaption of technologies for the world's 800 million small farmers.

Resilience, flexibility and policies that favour R&D investment in staple food research and efficient input use will be the pillars on which future food security depends. Darwin, whose 200th birthday was celebrated in 2009, 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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