CAN TECHNOLOGY DELIVER ON THE YIELD CHALLENGE TO 2050?

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ABSTRACT

This paper focuses on the yield prospects of wheat, rice and maize since these cereals dominate human diet, and since continued yield growth is considered the major route to meeting future global demand for food, feed and fuel. We define for a region farm yield (FY), attainable yield (AY, as reached with the best technology and prudent economics), and potential yield (PY, yield with the best varieties and agronomy and no manageable biotic or abiotic stresses). FY progress is a function of progress in PY and in closing the gap between PY and FY (we express this gap as a percent of FY). Globally wheat and rice annual yield increases (as a percent of current yield) are falling and are now just below 1 percent, while that for maize is 1.6 percent. For rice and wheat, the growth of yields in absolute terms (kg/ha/year) are also falling in developing countries. Global demand modelling to 2050 predicts large real price sensitivity to yield growth rates, with significant price increases if current rates cannot be increased.

FY, PY and yield gaps are examined in more than 20 important "breadbasket" regions around the world. For wheat annual PY progress currently averages about 0.5 percent, and the yield gap 40 percent (range 25 to 50 percent), while for rice PY growth is also about 0.5 percent while the yield gap averages 75 percent (range 15 to 110 percent). Maize is distinctive with a current average PY growth of around 1 percent and a yield gap which ranges from around 30 percent (Iowa, some uncertainty with PY) to over 200 percent (sub-Saharan Africa). A yield gap of 25 percent or less probably implies that FY is approaching attainable yields, AY. Yield gaps tend to be larger in developing countries, and seem to be closing only slowly except in the case of maize in Iowa and major cereals in Egypt.

Prospects for yield gap closing are discussed. A multitude of constraints can reduce FY, ranging from infrastructural and institutional ones bearing upon farm gate costs and prices and farmer skills and attitudes, to diverse technical constraints. The resolution of the latter in turn depends largely on agronomic and breeding interventions (e.g., better resistance to biotic stresses), though these must be resolved in concert with the other constraints if they are to have significant impact in resource-poor farmers' fields. Yield gap closing must be a priority for maize in sub-Saharan Africa.

Prospects for PY increase are discussed. PY gain is increasingly related to greater biomass production, implying greater efficiency of utilization of solar radiation. Recent progress appears to have raised this efficiency, while the theoretical limit still appears to leave scope for further increase. In addition PY in water-limited situations (PY_w) will depend on further harvest index increase. In rice and wheat heterosis offers prospects for yield gain. We remain skeptical of the medium-term prospects of genetic modification (GM) for yield *per se*, especially PY, but recognize that existing GM crops often deliver higher yields because of gap closing benefits (such as reduced pest losses). New molecular tools for selection show promise for increasing breeding efficiency, but the marginal cost of yield gains is likely to rise. Strong private investment in breeding, as seen with maize, could play a bigger global role, accompanied by facilitating policies.

We recognize in addition the importance of input efficiency and total factor productivity (TFP) for determining real prices, while prices of non-renewables (energy for traction and N fertilizer; phosphorus) are a relevant concern. TFP in agriculture continues to grow, and many examples confirm the general synergy

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amongst modern input technologies that achieve not only greater yield but also greater resource use efficiency (e.g. N, P, water, fuel, labour). There are also large gaps in input use efficiency that offer much scope for improved crop and resource management to deliver more with less. Investments in research and development, farmers' information and skills, and good policy drive this process, and will determine future success or failure.

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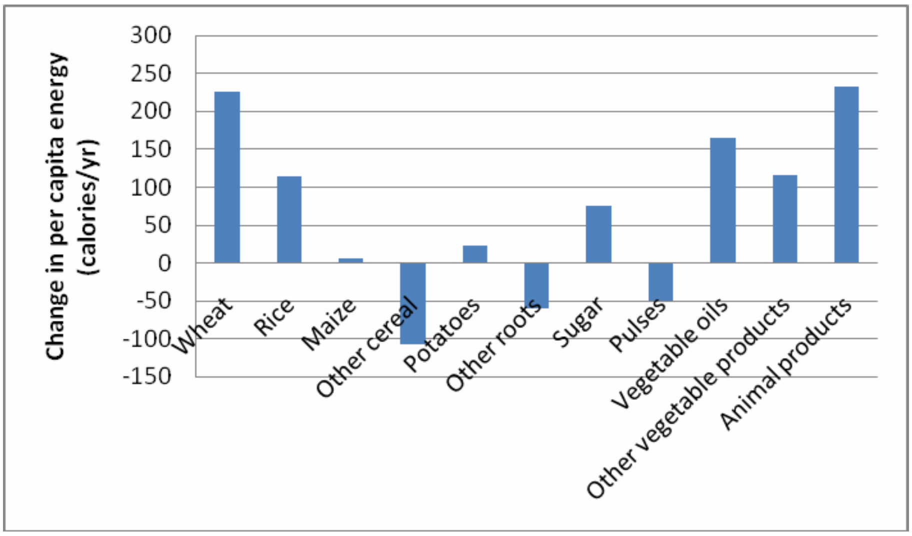
INTRODUCTION

Projecting crop yields, especially 40 years ahead, is fraught with uncertainty. Yet 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 paper is whether this decline means that we are reaching a technological plateau for crop yield, or whether there are still large unexploited sources of yield gains either on the shelf, or in the research pipeline.

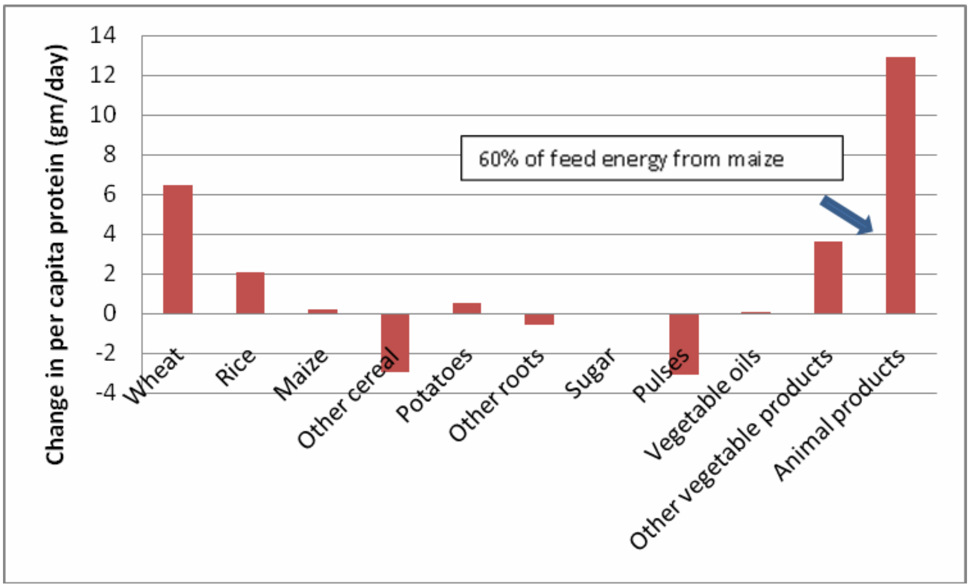
This paper addresses these questions through the analysis of cereal yields and productivity. It does so by tracing recent sources of growth and identifying future technological opportunities in terms of raising the potential yield, as well as closing gaps between existing yields and those that could be economically attainable by farmers. We focus 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 accounted for about half of the increased per capita energy intake in developing countries since 1960 (Figure 1.1). Maize has been the major source of energy to support the rapid increase in consumption of animal products (Figure 1.2) accounting for over 60 percent of energy in commercial animal feeds, as well as 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, we also recognize that diversification of food production is needed and a comprehensive review would include relevant data from roots and tubers, pulses and oilseeds. Some of these crops show declining trends, but remain critical to food security of millions, while others such as potatoes, sugarcane, soybeans, canola and oil palm are booming commercial crops serving multiple uses for food, feed and fuel.

Figure 1.1: Sources of increased per capita calorie consumption, developing countries, 1961-2003



Source: FAOSTAT

Figure 1.2: Source of increased per capita protein consumption, developing countries, 1961-2003



Source: FAOSTAT

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

Ultimately we are interested in the potential for sustainable productivity growth since it is the effects of productivity on food prices that have major welfare implications for poor people. This leads us 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.

We employ both a global and local approach to assessing crop yields. Changes in global yields are of course important for global food security. In a globalizing world, many countries will increasingly depend on trade to provision their food needs which should encourage production in the lowest cost regions, barring significant trade barriers. However, there are many situations where trade will be inadequate to assure food supplies. The "megacountries," China and India, have little choice but to produce most of their staple foods, especially rice, given relatively small, thin world markets in relation to their huge domestic markets. In Africa too, poor infrastructure, landlocked location, and lack of foreign exchange necessitate that much of the food be produced near where it is to be consumed. The high population growth in some of the more densely populated African countries places additional urgency on accelerating domestic production (e.g. projected population of Ethiopia of 185 million in 2050). The 2008 food price spike induced in part by export bans as well as rising energy costs for long-distance transport will likely lead many other countries to put a premium on local supplies.

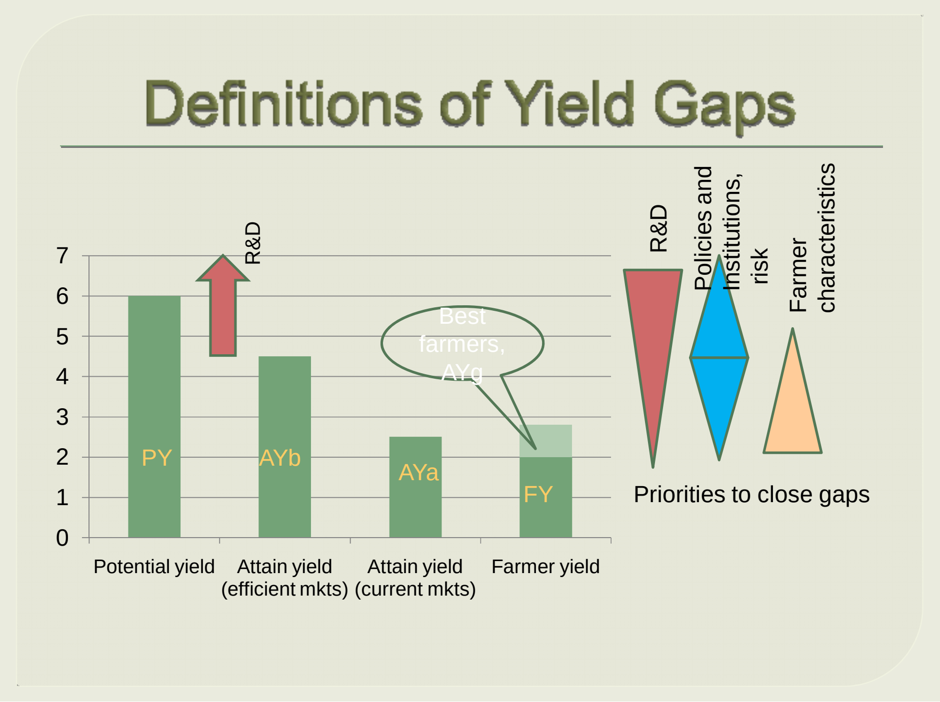
2. DEFINING KEY CONCEPTS

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

2.1 Yields and yield gaps

There are a number of measures of crop yields, which here means weight of grain harvested per unit field area at a standard moisture content (Table 2.1). The starting point is average farm yield (FY), from which we work upwards to attainable yield (AY) and then potential yield (PY). We include water-limited potential yield (PYw) because it is a sensible yardstick where crops receive on average only low to moderate water supplies (say < 75 percent of potential evapotranspiration). For increasing FY, the objective of this paper, both increasing PY (or PYw), and closing the yield gap, are important, and somewhat different interventions operate on these two steps. The overall gap PY to FY is considered in some detail because it is often easier to measure, but the key gap, the economically recoverable yield gap under current economics, is less, being AYa – FY (Figure 2.1; Table 2.1). Another gap AYb -AYa is the attainable yield gap under efficient institutions and markets (AYb), ultimately linked to world prices, less the AYa : this gap is often positive but can be negative where prices are subsidized to help farmers. Note that throughout this paper yield gaps are expressed as a percent of FY, for better comparability with the basis on which demand growth is estimated.

Figure 2.1: Schematic view of interesting yield gaps and ways to close them



Progress in potential yields, PY (or PYw the water limited potential yield), 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. There is considerable evidence presented in Section 4 of this paper that $\Delta FY/FY \approx \Delta PY/PY$. However, much will also depend on interactions between genotype and management (Fischer, 2009). Generally PY progress has exploited positive interactions between the genetic and agronomic routes for improvement in yield. The increase in yields of semidwarf wheat and rice varieties at higher levels of management is, for example, significantly more than that of the tall varieties they replaced. In advanced systems however yield increase from agronomy alone, and from these positive interactions, appears to be slowing, although the ongoing synergy between increase maize yield potential and plant population is one exception (Evans and Fischer, 1999).

Table 2.1: 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 or sometimes crop models
Economically attainable yield assuming efficient markets/institutions.	AYb	Optimum yield given prices that would prevail in efficient markets with well functioning risk insurance markets	On-farm experiments, or sometimes crop models
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 vars., well monitored crop contests
Water-limited potential yield	PYw	Maximum yield under normal rainfed conditions, removing all constraints as for PY except for moisture	Highly controlled on-station experiments or crop models or crop contests
Theoretical yield		Maximum theoretical yield for prevailing solar radiation based on prevailing knowledge of crop physiology and photosynthetic efficiency	An accepted estimate is 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 more by farmers' access to information and technical skills, while higher order yield gaps reflect opportunities for research as well as broader policy and institutional constraints. Figure 2.1 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 yields across farmers and fields, around the average FY in part due to site and season differences.[2] Often the distribution is negatively skewed (e.g. Lobell et 2000), but it is not clear how to relate such distributions to the prevailing AYa and PY. One might expect a proportion of farmers to always reach AYa, and a few to reach PY; crop contests that measure crop yield properly on sufficient field size (say > 4 ha) usually give very high yields which, in the absence of better sources, we have sometimes taken as the prevailing PY, but it is important to know whether the natural resource base of the winning fields (that part of the field which cannot be changed with good management) is representative of the region. Similarly, experimental stations may be in more favorable sites, so that some of the gap to reach PY can be due to site characteristics. In addition, optimum management is in part a function of seasonal conditions that are not known at the time of decision making, so that part of any yield gap is random—the interaction between management (including variety choice) and seasonal conditions.

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

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

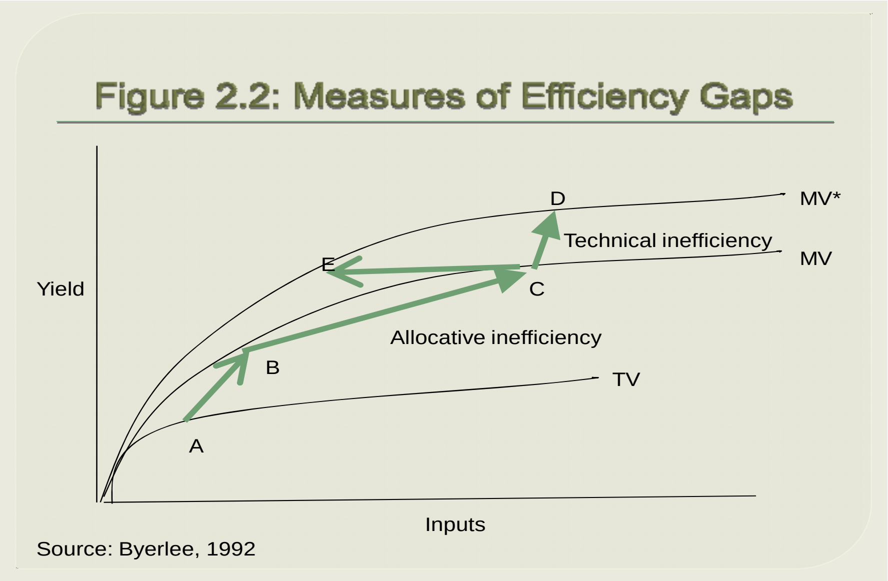
2.2 Efficiency and efficiency gaps

For reasons of both productivity and sustainability, we are 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 technical and allocative efficiency. Technical inefficiency refers to failure to operate on the yield frontier—that is 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 and one with considerable empirical support is given in Figure 2.2.[3] During the Green Revolution, farmers adopted modern varieties that shifted their production function from TV (traditional varieties) to MV (modern varieties). At the same time, farmers adopted modest levels of fertilizer and other inputs to reach point B. Initially however, due to risk, lack of knowledge and skills, and resource constraints, farmers did not fully exploit the technology, using inputs at suboptimum levels.

Figure 2.2 Measures of efficiency gaps (Byerlee 1992)



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. However, farmers still tended to operate considerably below the production frontier, 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 toward, say, D. Or with appropriate incentives or regulations (e.g. on input pollution), farmers may move to E reducing input use without sacrificing yields. The yield frontier MV_1^* may be defined in terms of the highest production achieved from a given level of inputs in a population of farmers, or it may be defined 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 et al., 2002). Of course, MV_1^* is not static but shifts upward with the release of new technologies, especially newer generations of varieties. It may also shift downward if there are serious long-term problems of resource degradation.

Yield gaps and efficiency gaps are often measuring 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

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

using above optimum input levels. As for yield gaps, factors related to farmer characteristics and system-wide constraints explain variation in efficiency across farmers and fields. 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.

2.3 Total Factor Productivity (TFP)

Ultimately, we are interested in gains in total factor productivity (TFP), as a major determinant of long-term price trends - most productivity increases have been 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 the component relating to changes in inputs, and a change due to productivity growth. The primarily 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 gaps, AYa – FY, institutional change or better infrastructure that closes yield gap, AYb – AYa, or related interventions to narrow efficiency gaps, by reducing input costs. Thus TFP is a composite measure of gains in closing gaps.

3. 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 required growth in yields to meet the world’s food, feed and fuel needs in 2050.

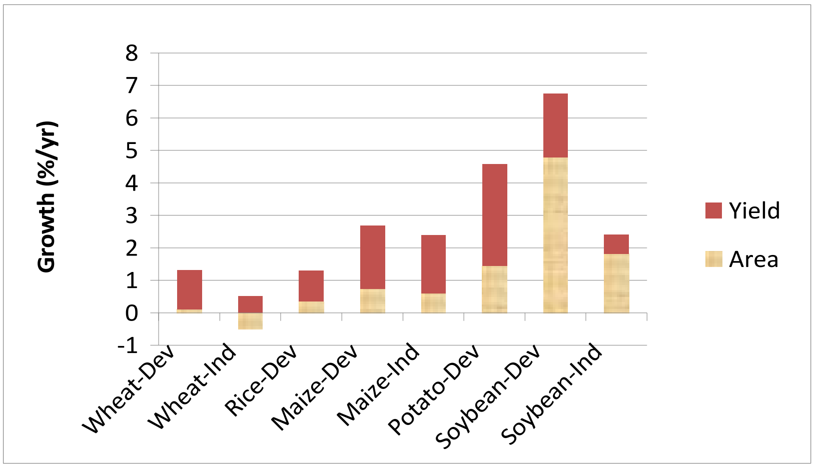
3.1 Recent change in crop area and key inputs

Land and water inputs are examined fully elsewhere in the conference, but being critical to our analysis they are mentioned briefly here. Area growth has only been a significant source of production growth in recent decades in Latin America and sub-Saharan Africa. Wheat area has fallen in industrial countries, while rice area has increased at only about 0.3 percent annually since 1990, and is actually falling in China, Republic of Korea and Japan. However, maize area has expanded consistently at over one percent per year in both developing countries (driven by livestock feed) and industrial countries (driven by biofuels, mainly in the United States of America). Even so, yield growth has been the dominant source of production increases even in maize (Figure 3.1).

Other crops have also been dynamic too. Potatoes, traditionally a staple food of much of Europe, are now grown more extensively in developing countries. Due to 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 3.1).

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 overall annual yield growth of 1.1 percent for cereal yields from 1991-2007.

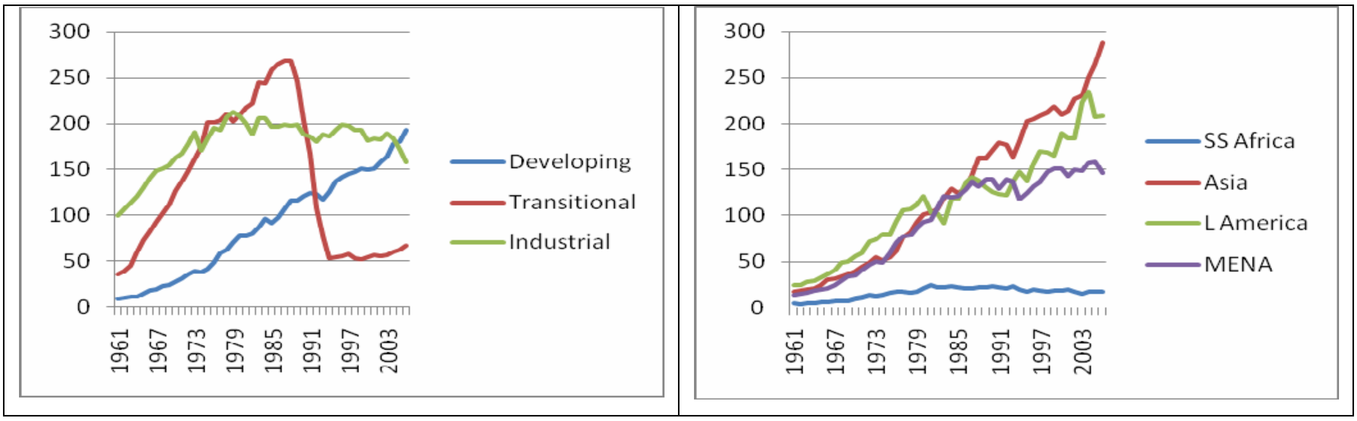
Figure 3.1: Contribution of area and yield to production growth, 1991-2007



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 (Bruinsma, 2003; Heisey, 2007). Developing countries now account for 68 percent of total fertilizer use. Its use has continued to increase by 3.6 percent per year over the past decade, which would still account for a significant share of yield growth.[4] Using a measure of agricultural area standardized for land quality (Fuglie, 2008), fertilizer use per irrigated-equivalent hectare is also now higher in developing countries than in industrial countries (Figure 3.2).[5] Globally, fertilizer use has plateaued due to a decline in fertilizer use in industrial countries, and a dramatic fall in the countries of the former Soviet Union after those countries moved toward a market economy.

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

Figure 3.2: Trends in Fertilizer Use (kg total nutrients per irrigated equivalent ha) by global region, and by developing region (1961-2006)



Source: FAOSTAT, N+P2O5+ K2O. Irrigated-equivalent area is computed following Fuglie (2008) based on a weighting of the relative productivity of rainfed, irrigated and pasture lands.

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

[5] 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).

Box 3.1: Fertilizer Use on Cereals

Wheat, rice, and maize account for about half of all fertilizer consumed globally. Data on fertilizer use for some countries for some years is provided in Table 3.1. The very high rates in some countries such as China suggest little scope for further intensification, and huge scope for improved efficiency. Indeed environmental pressures are likely to lead to pressure to reduce fertilizer use in many countries in Asia.

Table 3.2: Estimated fertilizer use (kg total nutrients/ha and kg N/ha) for wheat, rice and maize, selected countries, 2006

	Total nutrients (kg/ha)			**Nitrogen (kg/ha)**		
	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	118			84		
Argentina	77		79	44		46
Brazil	101	95	127	40	29	49
United States of America	129	250	269	86		152
EU-15	186		373	135		227
Poland	142			90		
Sub-Saharan Africa		10	38			
World	128	155	153	87	101	98

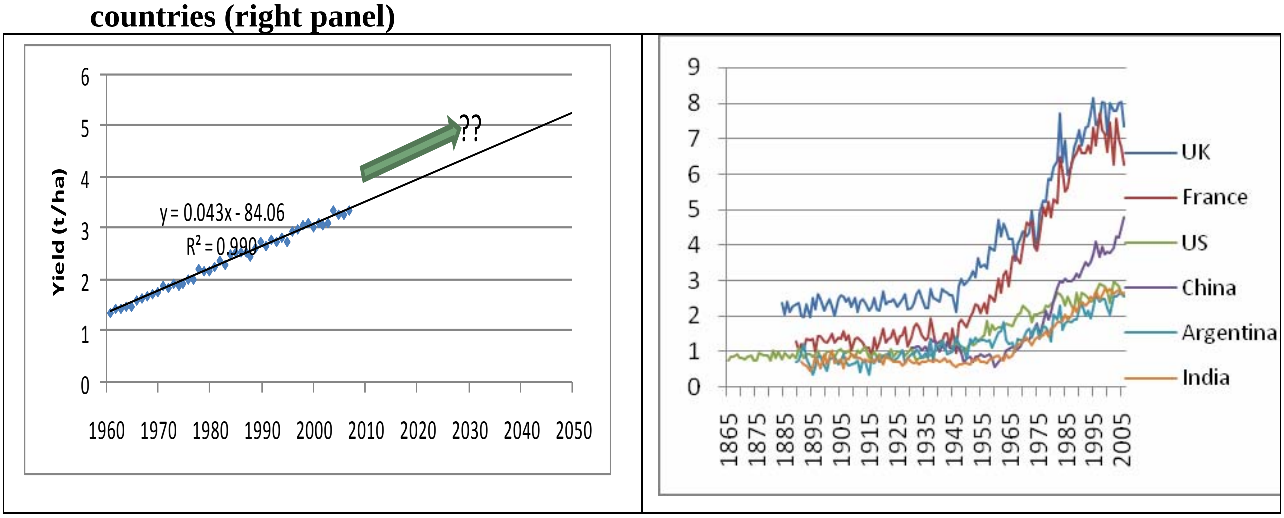
Source: Heffer, 2008; sub-Saharan Africa data from Heisey and Norton (2007) for the late 1990s.

Growth through intensification of fertilizer and irrigation use is no longer important in industrial countries. In addition, fertilizer use and irrigation are already high in some Asian countries, especially China, so that their future contribution to yield growth will be modest at best (Box 3.1). However, there are still major regions of the developing world, especially sub-Saharan Africa, where input intensification is at an early stage. Also Russia, Ukraine and other transitional countries are already reversing the collapse of input use, providing scope for more rapid yield growth in the future.

3.2 Recent yield progress (FY)

Over the past five decades, global cereal yields have grown linearly at a constant rate of 43 kg/ha annually and with very low variability around the trend (Figure 3.3). However, this is a sharp departure from relatively stagnant yields in earlier periods (Figure 3.3). Note that linear growth in Figure 3.3 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 only 0.8 percent per year growth then.

Figure 3.3: Long-term trends in cereal yields globally (left panel), and wheat yields in selected countries (right panel)

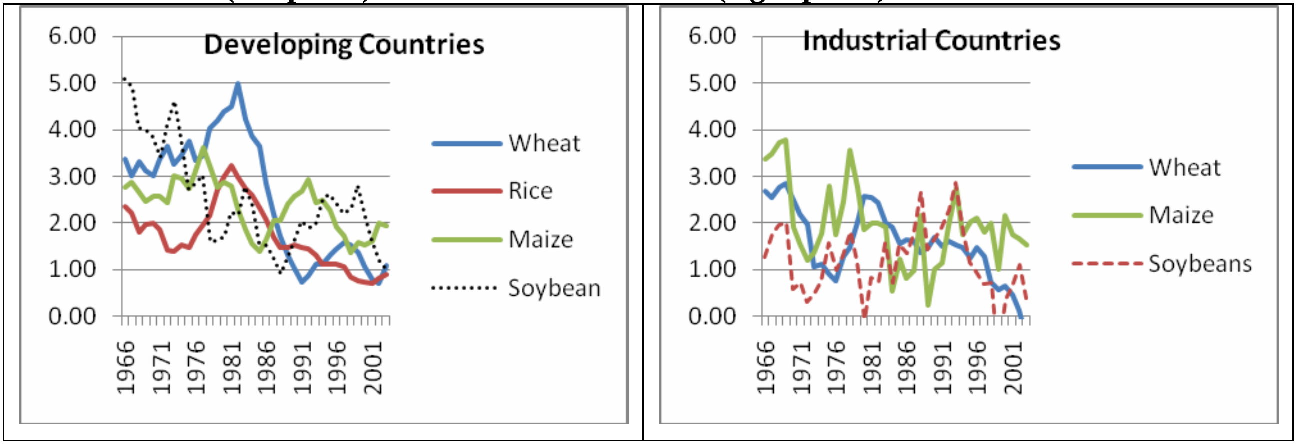


Source: FAOSTAT. Wheat yields updated from Pardey et al. (2007).

The aggregate global picture disguises important differences by region and crop. Developing countries experienced a sharp increase in yield growth with the Green Revolution and then a sharp drop off. The ten-year moving average growth rates for wheat and rice in developing countries has declined from the mid-1980s to about one percent annually in the most recent decade (Figure 3.4). Yield growth of wheat in industrial countries has also slowed and in the most recent decade fell to zero. The trends for maize, although showing some decline in growth rates in both developed and developing countries, are not nearly so pronounced.

At the regional level, Latin America has had the best yield performance for all cereals since 1991, averaging 2.5 percent annually. The lowest have been sub-Saharan Africa and surprisingly East and Southeast Asia, each around 1.2-1.3 percent annually. In one sense, there is some good news in both—sub-Saharan Africa has had a sustained period of modest yield growth from a very low base, and East and Southeast Asia have already have high yields of 4.8 t/ha so even this modest growth rate represents an achievement.

Figure 3.4: Ten-year moving average yield growth rates, wheat, rice, and maize in developing countries (left panel) and industrial countries (right panel)



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

There is also evidence of a slowdown in absolute yield growth for rice and wheat. We therefore tested the coefficient, c, of the quadratic term of absolute yield trends 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 analyzed was from 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. In the case of 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 and South 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.

In sum, 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 among regions, Latin America has been the star, partly because maize is the most important grain in the region. As well as exponential growth rates, looking at absolute growth aids the interpretation of trends.

3.3 Scenarios to 2050 and the future yield challenge

Against this background, what rate of yield growth is needed to meet world food needs of the 9.2 billion people that is the projected world population in 2050? Studies by Rosegrant *et al.* (2008) at the International Food Policy Research Institute (IFPRI) and Tweeten and Thompson (2009) provide recent analyses of this challenge.

Global demand and supply prospects will be examined in some depth elsewhere in this conference. Demand for grains is largely determined by population and income growth, with the recent addition of demand for biofuels. At a 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 products. Livestock in turn drive demand for feed grain, especially maize. In addition, maize and to a small extent wheat are used as feedstocks for biofuels. IFPRI projects that this demand for grain for biofuels will continue to increase to 2020-25 before leveling 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/capita of mostly maize for biofuels, 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 t. This derives from projecting the linear annual yield growth of 43 kg/ha suggested in Figure 3.3 over the whole period (1.4 percent growth exponential initially becomes 1.07 percent over the whole period).[6] Their middle estimate of demand growth give an increase of 79 percent by 2050 (1.17 percent exponential over whole period, world population of 9.1 billion in 2050). Thus there will be a projected supply deficit in relation to demand, that implies an increase in weighted real agricultural prices of 44 percent by 2050 to "clear the market".

Using mid-range (baseline) estimates of population (again 9.2 billion by 2050) and income growth, and biofuel demands, Rosegrant et al. (2008) project an overall increase in cereal demand of 1.048 billion t (56 percent) in 2050 from a 2000 base. That implies an average growth of 0.9 percent over the period, but they 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 m ha, as loss of crop land and crop diversification in industrial countries and in Asia cancels area expansion in Latin America and sub-Saharan Africa. Water available for agriculture also hardly increases due to competition from non-farm sectors, declining groundwater tables in the bread baskets of India and China, and likely higher energy costs for irrigation (Molden, 2007; Tweeten and Thompson, 2009). Some 60 percent of global cereal production is now from irrigated areas, and with competition within those 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 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 IPCC is not expected to have a significant effect on global yields by 2050 (IPCC, 2007), since yield gains in some regions (mostly temperate) balance losses in other regions (mostly tropical). The impacts of climate change will be addressed in more depth elsewhere in this conference.

The IFPRI yield projections are based on the FAO expert opinions disaggregated by country and agro-ecological zone (Bruinsma, 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 (Bruinsma, 2003).

The global average annual absolute rate of yield gain in the Rosegrant *et al.* (2008) projections is 37 kg/ha, 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—91 percent for wheat, 60 percent for rice and 97 percent for maize from a 2000 base. Besides, developing countries will increasingly depend on imports of cereals (and oilseeds) from industrial countries, Eastern Europe (including Russia), and Brazil and Argentina.

Projections are only just that, and the overall results are quite sensitive to the assumptions. In particular, Rosegrant *et al.* show that with a 13 percent increase in public investment 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 downward trend characteristic of much of the past century and could almost halve the number of malnourished children by 2050. By contrast, a 0.4 percentage point lower yield growth (to 0.61 percent) would lead to a more than doubling of real cereal prices, to around $600/t (US2000 dollars) and stagnation in the number of malnourished.

These studies have two major implications for our analysis of future yield perspectives. First, a continuous linear increase in yields at a global level following the pattern established over the past five decades will not be sufficient to meet food, feed, and fuel needs—that is, future demands at today's real prices or lower. The world will need to do better in the next forty years. Second, the outcome is quite sensitive to yield projections. An increase of 0.4 percent percentage points can reverse price trends. While this sounds like a relatively modest goal, they are exponential growth estimates, and require an increase in current absolute yield growth rate of more than one third. This cannot be taken for granted, especially since aggregate growth rates in both percentage and absolute terms are as we have seen clearly in a declining phase (except for maize) and input growth may make a much smaller contribution than in the recent past.

4. SOURCES OF YIELD GAINS IN THE BREADBASKETS

This section reviews recent progress in different measures of yields through a series of case studies in some of the major breadbaskets of the world. The full details of the case studies are reported elsewhere (Fischer et al., forthcoming) and only summary statistics are provided here.

The case studies indicate the depth of analysis which is necessary if we are to understand what is happening currently to crop yield on the farm (FY), which in turn is driven (i) by progress in potential yield (PY) arising from new agronomy and increasingly from new varieties, and (ii) by the adoption of these new technologies which narrows the gap between FY and PY (expressed here as a percentage of FY). Our studies reveal considerable diversity between cases, diversity based largely on crop species, agroecology, and stage of economic development.

In all cases estimates of PY and its rate of change were difficult to estimate, especially for crops under low to moderate rainfall (i.e. PYw), and because it is important that the PY or PYw for a region comes from crops with the same natural resource endowment as the region has on average. The estimates of current PY came 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, since older varieties often become more susceptible with time. Progress is calculated simply by plotting yield against year of release for varieties released in the last 20 or so years; always relationships were closer to linear over this release period than any other response shape. Note that this represents PY progress under advanced agronomy, and hence contains the genetic gains plus the usually-significant genotype by management interaction gains (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 global CO_2 increase, which for C3 crops like wheat and rice, probably currently adds 0.3 percent per annum to FY progress (Tubiello et al., 2007). However, PY growth estimated from trials of side-by-side comparisons of varieties of different vintage is not inflated by increased CO_2.

Several cases from each major crop environment and stage of economic development should be examined if we want to properly sample and fully understand what is behind the aggregate numbers on FY, and to project with some confidence. Some researchers are using high resolution GIS and crop modelling approaches to deal with the challenge of bringing together all of the world's cropping regions (e.g. Harvest Choice, a program that includes IFPRI). But we believe that although we could benefit from a more extensive sampling, our approach is also an appropriate way forward, and we bolster the case study numbers below with other sources of data wherever possible. For illustrative purposes, some key case studies are described more fully below. This lays the basis for the discussion in the following sections of the two paths to further increase FY, namely reduction in the gap between FY and PY, and increasing PY.

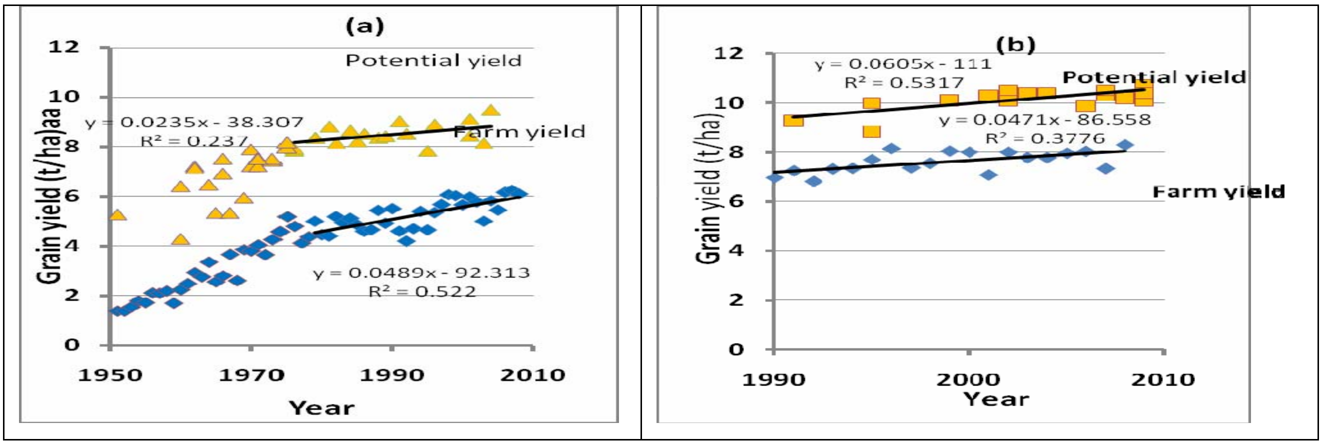
4.1 Wheat

Figure 4.1 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) and representative of 22 percent of the world's wheat area, found almost entirely in the developing world, while 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 et al., 2002). The Yaqui Valley has been a major target of the International Maize and Wheat Improvement Center (CIMMYT) and its predecessor's wheat breeding program for over 50 years; it is an environment similar to that for wheat in Pakistan and northwest India, and in Egypt: all have experienced a Green Revolution in wheat yields associated with improved varieties, irrigation and fertilizer.

In the Yaqui Valley, variety turnover is rapid and N rates have now reached 260 kg/ha; despite this, FY progress has slowed to about 49 kg/ha/yr over the last 30 years (Fig 4.1a). However, 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/yr or 0.3 percent per year. This is exactly the rate of progress seen in PY. Thus the yield gap is fairly steady at 50 percent of FY, somewhat surprising for a region of moderately-sized farms in a well developed agriculture.

The United Kingdom has one of the highest national wheat yields (just over 8 t/ha), with modern agriculture and an active private (breeding) and public research base. Excellent records of the Home Grown Cereal Authority from their protected variety experiments across the country give a good indication of PY. The rate of FY and PY progress has been fairly steady over the last 20 years at 0.7 percent 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).

Figure 4.1:Wheat yield potential and farm yield change in (a) Yaqui Valley of Mexico, and (b) in the UK (See relevant case studies for details)



Results of the Yaqui Valley and the UK and all other wheat cases are summarized in Table 4.1. Three other important wheat megaenvironments are included namely low to moderate rainfall spring wheat at low latitude (S4, about 16 percent of world area, equally distributed between industrial and developing countries), low to moderate rainfall high latitude spring wheat (S6, 21 percent of area mostly in industrial countries), and finally low to moderate rainfall winter wheat areas (W4, about 10 percent of area, equally distributed).

Table 4.1 shows a diversity of combinations of key parameters for wheat growing regions. The gaps given can be compared to those in the review by Lobell et al (2009). For wheat, they were able to summarize 12 estimations from developing countries in the 1990s, showing a FY range from 40 to 95 percent of PY, average 65 percent: expressing the gap as a percent of FY it averaged 55 percent, somewhat larger than our estimate for developing countries in Table 4.1. The difference could easily arise both from some lower estimates of FY (understandable give the earlier dates to which FY refers plus the inclusion of less advanced regions) and higher estimates for PY in the Lobell et al (2009) study.

Table 4.1 Summary statistics[a] for case studies of wheat yield change for case studies

Region and mega-environment[a]	Wheat Area M ha	Yield and gap, 2007 or 2008 t/ha, % FY			Rate of change, % relative to 2008 yield			Comment
		FY	PY	Gap	FY	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?	0	Case study
Haryana, India, S1	2.4	4.2	5.75	35	0.6	0?	-	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 Aust., S4	4.5	1.8	2.6	45	1.4	0.5	--	Case study
N Dakota, S6	3.4	2.5	3.7	50	0.9	1.0	0	Case study
United Kingdom, 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,b)
Kansas, W4	3.6	2.6	3.9	45	0.6	0.4	0	See case study

a. FY and its change are from FAOSTAT or USDA NAS. PY sources are given in Fischer et al.,(forthcoming), supplemented by reports from the literature. All rates of FY change are from linear trends over last 20-30 years, and 2008 yields are from linear trends; no curvilinear fits were superior, unless noted. Where possible FY trends have been corrected for secular weather change, but not for increasing CO2.
b. See text for key to megaenvironments.
c. ++ = gap increasing, 0 = no change, -- = decreasing

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 4.1. FY and PY progress 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 under rice), and high rainfall countries like Brazil also have good FY progress; acid soil tolerance and conservation tillage have been an important factor in Brazil's progress.

The environment S4 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 the Table, an excellent example of this. It is the only one where 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 area of the United States of America, most of Canada, eastern Russia, and northern Kazakhstan, along with north eastern China: it is almost entirely rainfed and moderately dry. North Dakota fits S6 and shows modest progress and a yield gap fairly typical of rainfed wheat in the industrial world.

The United Kingdom already discussed is probably reasonably representative of the favourable cool winter habit W1 environment, comprising Europe, Ukraine, southern Russia, the northern China plain and eastern United States of America.[7] In contrast to W1, W4 refers to the drier cool wheat environments, dominated by the Great Plains of the United States of America, the Anatolian Plateau of Turkey, and western China; it is represented in Table 4.1 by Kansas. Low PYw progress and the modest yield gap is similar to rainfed Western Australia. FY progress would likely be similar or better in the W4 regions Turkey and China, because of the lower yield base; also they would have good scope for FY gains from increasing the currently low adoption of conservation tillage in this erosion prone environment.

4.2 Rice

Figure 4.2 shows two case studies for rice, a crop almost entirely grown in developing countries (except for Japan and Republic of Korea). Central Luzon in the Philippines includes the irrigated wet season (I1, low radiation) and dry season (I2, high radiation tropics) environments which 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 only one percent of the world's rice area, equally found in industrial and developing countries.

FY in Central Luzon has been surveyed regularly by IRRI over the last 50 years; variety turn over has been rapid and over the last 30 years it has been entirely planted to modern varieties, and has reached high levels of fertilizer application (150 kg/ha N+P+K). After greater initial FY progress with the first modern varieties, yield progress since the late 1970s has been steady at 0.6 percent and a large gap (60 percent wet season, 100 percent dry season) persists when compared to PY at IRRI. The yield gap is smaller (about 35 percent) for wet season crops in Provinces adjacent to IRRI and PhilRice, Laguna and Neuva Ecija, respectively, where FY progress has almost ceased. PY progress itself has been very slow (0.2 percent) in IRRI, although disease and insect resistance, earliness and quality have improved markedly (Peng *et al.* 1999). The current dry season PY of 9 t/ha is corroborated by dry season yields of 9-10 t/ha for optimally-managed irrigated rice in tropical America under the FLAR program (G. Zorrilla, personal comm.). These estimates do not include the new tropical hybrid varieties just reaching farmers in the Philippines, and showing a 11-14 percent increase in PY in the dry season (Yang *et al.* 2007).

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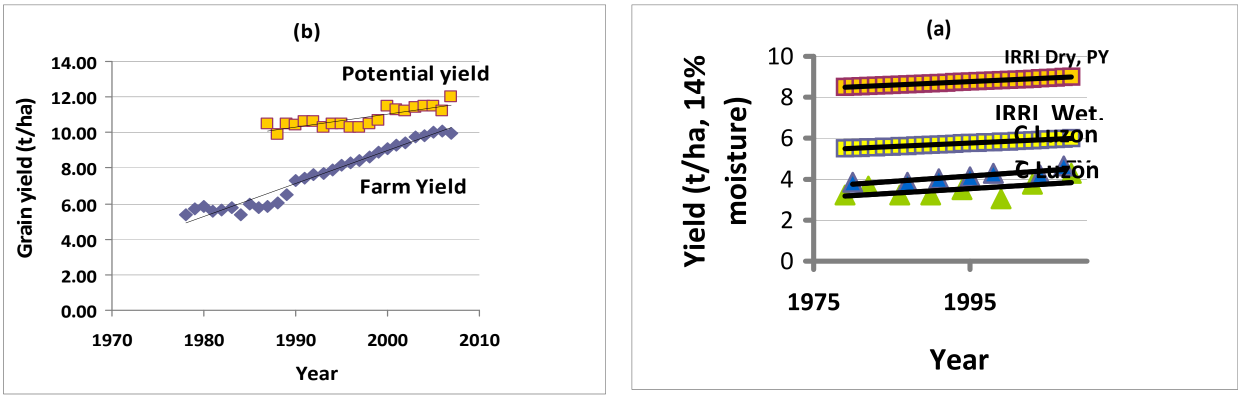
[7] However the eastern Chinese portion may have lower PY because of warmer grain filling.

Figure 4.2 Change in farm and potential rice yields in (a) Central Luzona[a], dry season and wet season, and in (b) Egypt



a. Potential yields for Central Luzon come from IRRI trials.

Egypt is noteworthy because of the contrast it represents: FY is the highest in the world (10.1 t/ha), exceeding that of California at 9.4 t/ha. FY has shown 1.8 percent growth in the last 20 years or so even as 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, now at about 15 percent of FY. It is suggested that the situation in Egypt reflects a strong research and extension effort; in addition there was price reform in the late 1980s which removed price disincentives for most crops including rice. These case studies and the others are summarized in Table 4.2.

Table 4.2: Summary statistics for case studies of rice yield change[a] in key regions

Region and megaenvironment[a]	Rice Area M ha	Yield or Gap 2007 or 2008 t/ha, %FY			Rate of change, relative to 2008 yield, %			Comments
		FY	PY	Gap	FY	PY	Gap	
Central Luzon wet I1	0.8	3.8	6	60	0.6	0.2	0	
Punjab I1	2.4	3.8	8	110	0.9	?	?	
China I1	29	6.2			0	?	?	FY growth ceased 1996
Japan I1	3	6.5	10	55	0.3	0.4	-	Area declining 1.7%
Central Luzon dry I2	0.4	4.5	9	100	0.6	0.2	0	
Egypt I3	0.7	10.1	11.6	15	1.8	0.7	--	Area increase 2%
California I3	0.2	9.4			0			
South Asia R1, R2, R3	28.5	1.8	3.6	100				IRRI, 2008

a. FY and its change is average farm yield from FAOSTAT or USDA NAS, PY sources are given in Fischer et al (forthcoming), supplemented by reports from the literature. All rates of FY change are from linear trends over last 20-30 years, and 2008 yields are from linear trends; no curvilinear fits were superior, unless noted.

The irrigated rice environment is well represented in Table 4.2 but it has not been possible to obtain reliable numbers for the other main rice ecologies, namely rainfed lowland (R1, 25 percent of area), rainfed upland (R2, 13 percent of area), and deepwater (R3, 7 percent of area), but Table 4.2 attempts to cover aspects of these for South Asia. Notable in Table 4.2 is the low FY growth, except for Egypt, in particular the low or zero growth of FY in China and Japan (and Republic of Korea, not shown). The situation prevails in China despite the 50 percent adoption of indica hybrids , and the reporting of hybrid yields up to 12 t/ha in the rice bowl of the eastern China plains (Peng et al 2008). Also notable are the slow PY growth rates.

The yield gaps in Table 4.2 can be compared to Lobell et al (2009) who summarized 41 estimates from developing countries of rice FY relative to PY: they ranged from 30 to 85 percent, with an average 60 percent. This converts to a farm to potential yield gap of 65 percent. They supplement these numbers with results from a modelling exercise for irrigated rice PY across Asia, concluding that for north east Asia FY was about 75 percent of PY (gap = 35 percent of FY) but in NW India only about 45 percent (gap = 120 percent).

In the case of rice where the irrigated environments are fairly distinctive and dominant, we get another estimate of yield gaps by simply comparing regional or national yields for like crop agroecologies, and assuming that the highest yield represents at least the current global attainable yield (AY), or at least a conservative estimate of it. For example in I3, the current national average yield in Egypt at 10.1 t/ha: 9-10 t/ha can be seen as the appropriate AY for intermediate latitude countries with cloud-free summers and an absence of chilling at meiosis, as experienced by Iran (current yield 4.9 t/ha), Uzbekistan (3.4 t/ha), or Chile (5.5 t/ha).

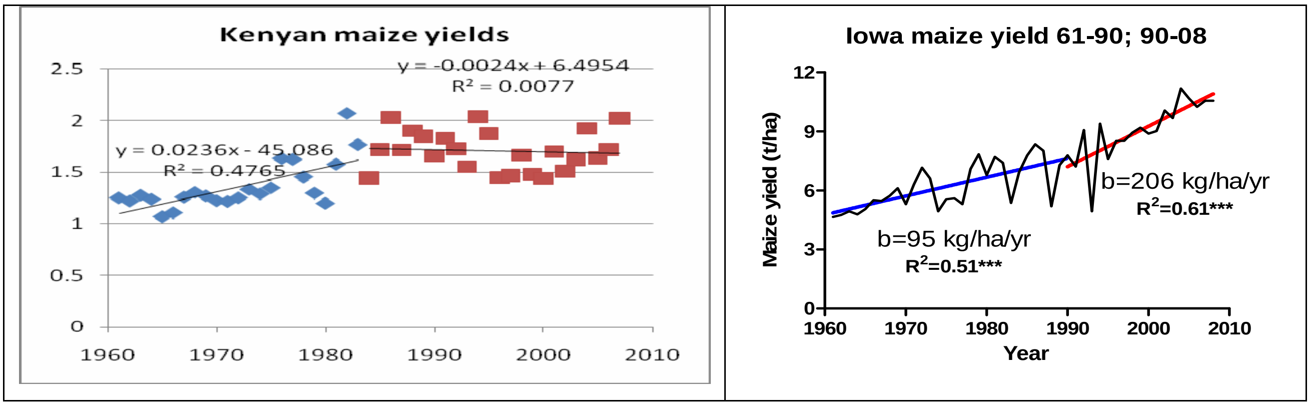
4.3 Maize and related crops

CIMMYT has defined useful megaenvironments for maize in the developing world to which we have added the industrial countries. One case study is Kenya which encompasses all the low latitude maize environments, namely tropical lowland (M1, 32 percent of world area), subtropical and mid altitude (M2, 13 percent of area) and highlands (M3, 4 percent); all are to be found in developing countries. Generally these are relatively humid environments with maize tailored to fit the wet season, but being relatively susceptible to water shortage, drought stress is not uncommon: 21 percent and 14 percent of the area in the tropics and subtropics, respectively, are estimated by Heisey and Edmeades (1999) to be “often stressed”. The second case study is Iowa in the United States of America, representative of the relatively humid (or supplementally irrigated) favourable temperate environment (M4) which contain 51 percent of the world’s maize area, equally distributed between industrial and developing nations.

Maize in Kenya is complicated because of the diverse environments, but 75 percent of the maize is in the more favourable M2 and M3 environments above 1100 meters. Kenya was a pioneer in hybrid maize and other farmer support but this fell away in the early 1980s, and yield growth ceased or even fell after 1980 (Fig 4.3 a). In the 1990s privatization of the fertilizer supply took place and fertilizer use has slowly grown to reach around 45 kg/ha (N+P+K); FY, after falling in the early 1990s, appeared to start growing in the mid 1990s, averaging 36 kg/ha /yr since 1996, to give an impressive 2.1 percent current rate of growth (before the problems of 2008). Many factors still constrain maize yield in Kenya, including degraded soils, insufficient nutrient supply whether from fertilizer or manure, risk associated with drought especially in marginal areas to which maize is spreading, weeds like Striga, and intercropping (which is not in itself a constraint). Thus PY in the favoured M2 and M3 areas is so far above FY (yield gap nationally is at least 200 percent) as to seem irrelevant. However PYw 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), and these have shown good progress in trials throughout southern Africa (Bänziger et al , 2006); recently genetic modification (GM) approaches for drought tolerance have been included.

Iowa State grows 5 M ha of maize largely in one-crop per year rotation with soybeans. FY progress has been impressive for many years (Fig 4.3 (b)); progress accelerated around 1990 and currently it is 206 kg/ha/yr or 2.0 percent of the impressive 10.5 t/ha in FY. 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 GM corn varieties. Certainly herbicide-resistant maize favours conservation tillage and perhaps earlier sowing, and Bt maize may be giving resistance against yield losses not even recognized in the past (e.g,, root worm resistance). We struggled to estimate PY and its rate of change: farmer contests suggest PY currently around 17 t/ha, which would give a yield gap of 60 percent, perhaps surprising for advanced farming. The best hybrids in breeders trials appear to be reaching around 12-15 t/ha, so there is some confusion about PY in Iowa, which needs further study. These same breeders trials indicate current PY progress is about 1-1.5 percent per annum (e.g. Hammer et al 2009; Edgerton, 2009).

Figure 4.3: Changes in maize farm yields in (a) Kenya, and in (b) Iowa State[a]



a. Maize grain yield (14 percent moisture) Source: (http://www.nass.usda.gov/QuickStats/PullData_US.jsp).

These maize case studies and other useful maize data are summarized in Table 4.3. Some sorghum, millet and soybean data are also included. 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. Soybeans on the other hand is a unique leguminous oilseed often competing for the maize environment.

Table 4.3: Summary statistics for case studies of maize yield change in key regions, and for some key related crops

Region and megaenvironment	Area M ha	Yield 2007 or 2008 t/ha			Rate of change relative to 2008 yield, %			Comment
		FY	PY	Gap, %	FY	PY	Gap	
Maize								
Kenya M1, M2, M3	1.75	1.8	6[b]	200+ [b]	2.1	++	--	FY growth in last 12 yrs only
Sub-Saharan Africa M1-M3		1.6	4.1[c]	193[c]	0.8	?	?	Area increases
Brazil M2	12.5	3.6			2.6			
Iowa M4	5.3	10.5	12? 17?	15? 60?	2.0	1.0	?	PY from trials versus contests
United States of America 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			1.8			Area growth 4.4%
Soybeans United States of America M4	31	2.8			1.3			Area growth 1.5%

a. FY is from FAOSTAT or USDA NAS. All rates of FY change are from linear trends over last 20 years, and 2008 yields are from linear trends; no curvilinear fits were superior, unless noted.
b. Conservative expert opinion for PY across all environments
c. These are attainable yields (AY) from on-farm with best-bet technologies.

Notable in Table 4.3 are the relatively high FY growth rates, compared to wheat and rice, not only in Brazil, United States of America, China and Egypt, where hybrids dominate, but also 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 4.3 can be compared with those in the extensive review by Lobell *et al.* (2009), who cited nine tropical and subtropical maize cases (FY was 16 to 46 percent of PY, average 33 percent), as well as two reports from Nebraska, namely irrigated (56 percent) and rainfed (40 percent); these convert to gaps relative to FY of 200 percent (tropics, subtropics), and 85 percent (Nebraska, irrigated) and 150 percent (Nebraska (rainfed). These numbers are quite comparable to those in Table 4.3, and suggest that yield gaps are large for maize, compared to wheat and rice. But the Nebraska data is surprising and comes originally from Duvick and Cassman (1999). Lobell *et al.* (2009) later cite unpublished simulations of maize PY which indicate FY in Nebraska is 75 percent (irrigated) and 65 percent (rainfed) of PY, amounting to a gap of 35 percent (irrigated) and 55 percent (rainfed) of PY.[8]

In another approach, we can contrast the poor yields in M1-M3 environments in sub-Saharan Africa in Table 4.3 with those of southeast Asia (averaging over 3 t/ha across 8 M ha), and 3.6 t/ha in Brazil.

Yields of sorghum and millet in sub Saharan Africa are even poorer than maize probably partly reflecting area expansion into more marginal areas. In India millet is the direct target of ICRISAT's research effort: yield grows but area declines, while recent simulation modelling and on-farm demonstrations indicate PY to be 1.8 t/ha, suggesting a gap of 100 percent (Murty *et al.*., 2007). Soybeans, the direct competitor with maize, is showing remarkable yield and area growth globally, exemplified by Brazil and the United States of America.

4.4 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 with wheat and rice, crops where breeders must give more attention to grain quality traits and disease resistance than in the case of maize. In most situations there is a gap exceeding 30 percent between FY and PY, but it is as great as 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, but it has been difficult to get good estimates of PY progress. The gap between FY and PY appears to be large in maize, especially in sub-Saharan Africa where it easily exceeds 100 percent.

5. 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 having the same natural resource endowment. 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 that are constrained only by such considerations have been usefully defined as the attainable yield (AY, see Section 2), but we must bear in mind that AY is driven by farm gate prices, and these 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, a nation of modern farmers, institutions and infrastructure, and minimal subsidies nowadays, should approach AY: the 25 percent yield gap seen there between FY and PY (Table 4.1) is therefore one useful estimate of the minimum gap to be expected due to economics and risk. Another approach to AY is to look at the distribution of field yields within a region and assume that some proportion of the higher yields indicates AY, e.g. the mean of the top one third (Byerlee et al 1999), or the 9th decile (Yaqui Valley case study). This however has problems - first it is hard to get a

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[8] The discrepancy with the earlier report of 85 and 150 percent gaps comes from lower values of PY with simulation (e.g. 12.2 to 17.6 t/ha across Nebraska, irrigated). Also compared to our estimate of PY for Iowa from contests (Table 4.3) and current yields of contest winning crops in Nebraska, these simulations seem unrealistically low and we hold to the view that there is a substantial yield gap even in Nebraska even with irrigated maize.

large unbiased sample of field yields, and second yield variation may be due to variation in the natural resource base of the fields, not solely to that in exploitable factors.

In our case studies, we found only one yield gap smaller than that with wheat in the United Kingdom, namely 15 percent for rice 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 *et al.* (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 farmer decision making (especially in rainfed situations) may raise this estimate of the yield gap somewhat. If we are conservative and consider 30 percent as the minimum, above which there is scope for economic exploitation, then 14 out of the 17 cases shown in Section 4 appear to have an exploitable gap, some being quite large. As might be expected there is also a strong tendency for smaller gaps in industrial countries. Other things being equal, one might expect PY increases to be important for the future where the gap is small, and gap closing possibilities to increase as the size of the gap increases. Here we look at gap closing.

Issues of poor infrastructure, weak institutions and bad farm policy can create huge obstacles to the adoption of improved technologies, which are exhibited, in particular, 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 of the world, and higher still in inland landlocked regions (Morris *et al.*, 1997). Solutions lie with public investment in infrastructure and institutions, and sound policy, the lack of which has been a major contributor to the large yield gap in places like sub-Saharan Africa (e.g. Table 4.3); these have been widely canvassed elsewhere, we focus on those other (non-market) constraints which contribute to the exploitable yield gap (Table 5.1).

The second column (breeding) in Table 5.1 is pointing to ways targeted breeding can help close yield gaps, not by raising PY or PYw, but essentially by making varieties more resilient: since new varieties are generally adopted more readily than new management techniques, often being a less expensive option for the farmer and the extension organization, this is always a favoured route if the required genetic variation exists. In contrast to breeding, there is nothing new in the first and last columns of Table 5.1, these are technologies and policies which already exist in many parts of the world (although some might be refined with further research e.g. IT for small holders or seasonal forecasting), and all have had or should have positive impacts on FY where appropriate.

Without doubt the biggest role of plant breeding in gap closing lies in host-plant resistance. Oerke (2006) presented a meta-analysis of actual yield losses globally due to biotic stress (weeds, insects, fungi, bacteria and viruses) which averaged over 23 percent of estimated attainable yield (hence a greater percent of farm yield) across the major cereals (without any controls, potential losses were estimated to average 32 percent) (Table 5.2). This is part of the exploitable yield gap, and its reduction is the aim of host-plant resistance breeding. Conventional breeding is making progress by maintaining resistance levels in the face of evolving pest agents, while at the same time aiming to strengthen resistances. This has been recently documented globally in the case of wheat rusts (Brennan and Dubin, 2009). Others have pointed to the growing impact of transgenic insect resistance, particularly with maize (and cotton), and linked it to yields gains, as more effective less expensive host-plant resistance replaces insecticides. It would seem that scope for halving a global yield gap of around 30 percent of FY via better host plant resistance is good in the medium term (15 years), especially if transgenic resistance to fungal diseases which currently exist in a few cases, can be delivered.

Table 5.1: Constraining factors contributing to the farm yield-potential yield gap and their alleviation so that farm yield can approach the attainable yield corresponding to the current potential yield with realistic economics

Constraint	Resolution		
	Agronomic	**Breeding**	**Institutional/ infrastructural**
General farmer constraints			
Lack of farmer awareness or conviction or skill	On-farm demonstration	On-farm testing and selection	Education, media campaigns, extension
Risk aversion by farmer	Forecasts, tactical decision making (e.g., for N top dress)	Tolerance of extreme weather events, like drought, flooding, hail, frost, wind.	Insurance, favorable credit terms
Inadequate labour supply	Mechanization, reduced tillage, herbicides	Select for uniform maturity to favour mechanical harvesting	Facilitate labour migration; credit for mechanization
Technical constraints			
Lacking major long-term soil amelioration	Drainage, land leveling, 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 soil toxicities	Ameliorate (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 Zn uptake and utilization.	Input suppliers, quality control
Soil variation within and between adjacent fields	Diagnostics to aid adjustment of application rates	Greater tolerance of soil stresses	
Growing old varieties, or use of 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	Mechanize and reduce tillage to speed sowing.	Make available varieties with range of maturities; herbicide tolerant varieties	Policy to favour mechanization, contract seeding
Poor plant population	Better drilling procedures and machines, quality seed storage	More robust varieties (e.g. long coleoptile in wheat, more tillering)	
Diseases and pests, above and below ground	Biocides, sanitation, crop rotation.	Host plant resistance	Input suppliers, quality control
Weeds	Herbicides, cultivation, sanitation, crop rotation	Enhance crop plant competitiveness, herbicide tolerance	Herbicide quality control, release regulation
Poor water management in irrigated systems	Improve water application techniques and skills	Greater tolerance water shortage and excess	Efficient supply systems to farm
Long term soil degradation	Crop rotation, fertilizer, green manuring, farm yard manure, conservation tillage, zero tillage	Varieties adapted to biotic and abiotic stresses of high plant residue levels, and with good residue production.	Regulations ensuring land ownership by farmer

The Oerke (2006) meta-analysis also estimated actual losses due to weeds at ten percent (potential losses 33 percent). Modern varieties tend to be more susceptible to weed competition, so breeding has not helped until the advent of herbicide tolerant cultivars, firstly using natural resistance, then in the last 15 years, GM-based resistance. glyphosate ("Round-up") and glufosinate resistant GM 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. GM 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 developing world extension.

Table 5.2: Global estimates of potential crop losses without physical, biological or chemical protection, and actual crop losses as a percent of attainable yields of wheat, rice, and maize

	Wheat	**Rice**	**Maize**	**Wheat**	**Rice**	**Maize**
	Potential losses			**Actual losses**		
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

In any situation there are usually multiple constraints, and the challenge is to determine 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. This 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 nowadays by the use of remote sensing and ICT advances. It is noteworthy that in the industrial world the large commercial maize seed companies such as Monsanto and Pioneer employ more agronomy-extensionist than breeders to ensure that new varieties reach their potential in farmers' fields.

In the developing world the more traditional approaches remain, although with growing emphasis on farmer participation (Paroda 2004). Lobell *et al.* (2009) recount how IRRI conducted on-farm rice experiments in Asia in the 1970s to test high-inputs, learning that farmer yields 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 as the season unfolds, 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 surely that this is scientist-intensive expensive research, often taken over by the farmer and his advisers in the industrial world, and explaining why large yield gaps often persist in the developing one, where circumstances demand innovative approaches in order to reach the billion small farmers (e.g. Paroda 2004).

Very recently IRRI again looked at rice yield gaps, this time using expert knowledge to assess constraints and possibilities for rice in South Asia (IRRI, 2008). For this crop, FY is currently 5.1 t/ha over 34.3 M ha; it was estimated that on average yield was constrained 1.9 t/ha (37 percent) by yield limiting factors, which included nutrients (10 percent), diseases (7 percent), weeds (7 percent), water shortage (5 percent), and rats (4 percent). They predicted that the adoption of existing technology and ongoing breeding for robustness over the next 15 years would reduce the total loss by about one third, adding 35 kg/ha/yr or 0.7 percent each year to FY. The exercise was repeated for the 28.5 M ha of rainfed lowland and upland rice in South Asia with a current FY of 1.8 t/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 R, D and E (research for development, including extension) over the next 15 years, adding 19 kg/ha/yr, or 1.0 percent, to FY.

With wheat in the Yaqui Valley we have a recent concerted effort to understand the yield gap, PY-FY (currently 50 percent, Table 4.1), this time using the latest high-resolution satellite imagery to estimate field-level yields (Lobell *et al.* 2003) and supplement a long history of farm surveys. It was estimated from images over several years 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 over years totaled about 10-15 percent of FY, and would bridge about half of the gap to estimated AY in the Valley. It is interesting the N nutrition was no more than a very minor limitation, surveys and on-farm field work pointing to considerable scope with smarter N management for improved N fertilizer use efficiency, if not greater yield (Ortiz-Monasterio and Raun, 2008).

The persistence of large yield gaps in the developing world especially, draws attention to situations where these gaps have been closed. Rice in Egypt is an obvious example mentioned already. A second example of dramatic technology adoption, albeit with lesser 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) (rising from nothing in 1970 to 24 M ha in 2000). This was very much driven by farmer groups and the 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 north-west South Asia). A third success story amongst small poor farmers has recently appeared with winter maize in Northeastern India and Bangladesh.

We conclude by pointing out that despite individual success stories like rice in Egypt, yield gaps in general appear to be quite persistent and close only slowly; this happens even when gaps are well above that to be expected from economics and risk aversion and even when PY progress has slowed such that catch up through eliminating excessive lags in varietal adoption is not a big 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 maize in sub-Saharan Africa exemplifies. Elsewhere public sector agencies, in particular reaching the billion small farmers in Asia (Paroda 2004), aided by the private sector, in particular in Latin America, have made some inroads on the yield gap; they should continue to do so largely in proportion to the investments made, but there is also scope for innovation, for example based on modern ICT technologies (see Section 7). 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 advance through R and D, things need to be done locally, but it can be argued that the internet and mobile phones are relevant spill-in technologies that are playing a role which could greatly expand. Finally we point out that given the persistence of yield gaps it remains critically important to continue to lift FY through improved PY, the subject of our next section.

6. Increasing Yield Potential (PY)

We have seen that 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 by breeding synergies will certainly be discovered but are hard 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 increases in HI and adaptation of phenology, have already been made. Increasingly progress will probably depend on molecular and physiological knowledge of plant growth processes to better target breeding efforts for PY, although we should not forget that empirical breeding continues to make some yield progress. In this section we consider the prospects and avenues of increased PY under conditions of adequate water and under water-constrained (PY_W) conditions. Brief mention is also made of PY_N, or PY under nitrogen (N) limitations.

6.1 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).

$$PY = \text{Total aboveground dry weight (TDW)} \times HI \quad (1)$$

$$PY = \int PAR_i \times RUE \times HI \quad (2)$$

$$PY_W = \text{Transpiration (T)} \times TE \times HI \quad (3)$$

where $\int PAR_i$ is the integral of photosynthetically-active radiation (PAR, MJ)[9] intercepted by green tissue over the life of the crop; RUE, or radiation use efficiency, is the efficiency with which PAR_i is converted into above-ground biomass (g/MJ). For PYw, T is the amount of water taken up and transpired by the plant (mm); and TE is transpiration efficiency for creating dry weight (mg/g or kg/ha/mm). A parallel to equation (3) for PY_N, N-limited potential yield, can be written as N absorbed and NUE. There are many variations of these identities (Mitchell *et al.*, 1998), but they all point towards efficiency with which a limiting input (radiation; water, N) is captured, then used to create dry weight and how efficiently that biomass is converted to grain (HI). The concept of PY/day is also important, since 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 increased PAR_i and modest increases in RUE (Muchow and Sinclair, 1994; Bange *et al.*, 1997). Altered planting date or planting configuration also give small gains in PY and PY_W through better crop timing with respect to expected weather patterns. 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 US, where HI has remained relatively stable under favorable conditions and PY has increased because TDW has increased (Duvick, 2005). Typical values of HI are 0.5 – 0.55 under good conditions for modern winter wheat, rice and temperate maize varieties, but only 0.4 – 0.45 for spring wheat and modern tropical maize varieties (Johnston et al., 1986; Duvick *et al.*, 2004). There appears little scope for further increase in HI beyond 0.5 since the crop needs a stable structure to distribute its leaf area, to support its seeds, and to prevent lodging. There seems to be scope, however, 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/m^2 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)[10]. 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 around 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 later).

A key aspect of gains in PY in the past has been increased numbers of grains/m^2 of land area rather than changes in weight of individual grains (e.g. Bolaños and Edmeades, 1996; Fischer, 2007). Seed number/m^2 is related to crop growth rate from 20-30 d before flowering to 10 d after flowering in all three cereals (see later), and to the ability of the variety to partition assimilate to the developing ear (Andrade et al., 2000;

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[9] 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 et al, 1998). We use PAR throughout.

[10] 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 high temperature on occasions are important. They concluded that yield gains with selection have come about because of better tolerance to these "minor stresses," rather than increase in yield potential *per se*. At modern planting densities (around 100,000/ha) plants are also under substantial stress from crowding.

Shearman *et al.*, 2006). Rice and wheat varieties with 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).

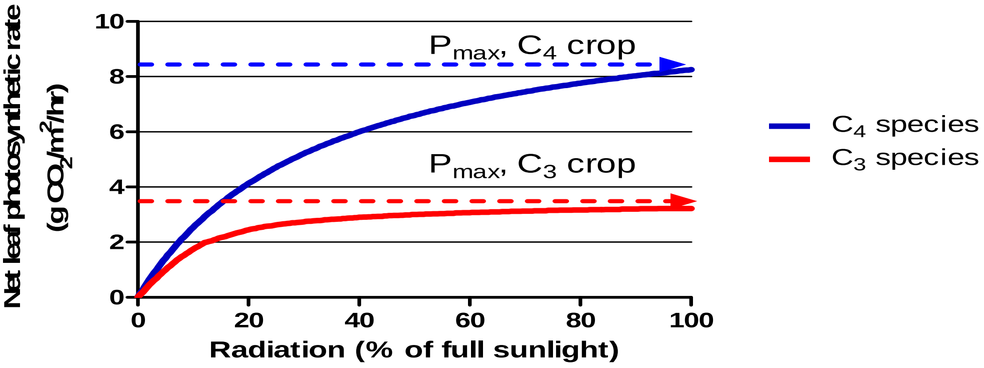
In summary, the likeliest routes to further increases in PY are through increases in RUE, or in PAR_i by extending the active life of leaves, but when it comes to PYw, preventing the common decline in HI when crops are under stress, is also an important possibility. But it is the challenge of RUE and its constituent components that 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…".

6.2 Increasing RUE

RUE is the ratio of gross photosynthesis minus (crop respiration + root dry matter) to radiation intercepted over time periods of 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 *et al.*, 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 (so-called Kranz anatomy) that sharply reduces CO_2 losses from the photorespiration observed in C_3 crops. As irradiance of the leaf increases, photosynthetic rate of C_3 species reaches a maximum (P_{max}) at a lower irradiance and at a lower value of photosynthesis than C_4 species, and therefore has a lower RUE (Fig 6.1), TE and NUE than a C_4 species. C_3 species however are generally better adapted to cooler conditions.

The main source of variation in RUE is species themselves, and P_{max} and RUE are positively associated. Although RUE increases relatively less for a given relative increase in Pmax, the exact relationship depends on how light is distributed down into the canopy. Mitchell *et al.* (1998) found that the average RUE values during vegetative growth under optimal conditions were wheat (2.7 g/MJ), rice (2.2 g/MJ), maize (3.3g/MJ) and soybean (1.9 g/MJ), 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 with selection (Lindquist *et al.*, 2005). 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 a theoretical maximum limit to RUE of 5.8 g/MJ (C_3 crops) and 6.9 g/MJ (C_4 crops).

Figure 6.1: Response of leaf net photosynthetic rate to radiation as a proportion of full sunlight for C_3 and C_4 species (after Loomis and Connor, 1992)



Since leaves spend much of their lives in shade, the likely route to improving yield potential is to increase RUE under radiation levels of 10-50 percent full radiation (Figure 6.1). 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/ground area. This results in lower irradiance at the leaf surface and hence a higher RUE, but there is little further scope for improving RUE via canopy structure in these crops since all the modern varieties have very erect leaves. Similarly Loomis and Amthor (1999) concluded that crop respiration is very efficient, with only modest prospects of improvement through targeted selection for low respiration rates.

Future increases in RUE through breeding are therefore likely to be through increases in Pmax; recent evidence suggests Pmax 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; importantly this progress in photosynthesis was measured during the critical period determining seed number. What kind of additional progress could be made by focusing on Pmax itself? One opportunity for dramatic changes in Pmax lies in genetic engineering of the leaf photosynthetic system, especially the central photosynthetic enzyme, Rubisco, by increasing its efficiency to capture CO_2, or increasing the supply of CO_2 or other limiting substrates to the enzyme. A very ambitious project underway at IRRI involves genetic engineering 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 one to four percent over the next 10 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). We consider these transgenic approaches to 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, amongst primitive wheats and wild relatives for more efficient photosynthetic machinery, bearing in mind that such wheats have already exhibited higher Pmax levels than modern varieties (Evans 1993).

6.3 Projections of PY

6.3.1 Wheat: a well-researched estimate of wheat yield potential for the United Kingdom (Sylvester-Bradley *et al.*, 2005; R. Sylvester-Bradley personal comm.) based on reasonable assumptions, including an RUE of 2.8 g/MJ and a HI of 0.6, while deploying stem dry matter as efficiently as possible to minimize lodging risk, resulted in 19 t grain/ha under well watered conditions; this could result in a 50 percent increase in average farm yields to around 13 t/ha by 2050.

6.3.2 Rice: Mitchell *et al.* (1998) predicted that conventional selection could result in a tropical and subtropical rice PY of 11.3 t/ha for IR72 maturity. On the other hand, the application of IRRI's "New Plant Type" principles in the large Chinese "super rice" breeding program has already given a 10-20 percent jump in PY to 12 t/ha in hybrids grown in lowland eastern China (Peng *et al.*, 2008). Sheehy *et al.* (2007) predict yields 50 percent greater than the present 9 t/ha if C_4 photosynthesis could be engineered into rice, and the relative advantage could rise as global temperatures increase.

6.3.3 Maize: It is difficult to find consistent PY projections for maize. Chile has the world's highest national maize yield (11.5 t/ha over 130,000 ha in 2005-07) and yields over 20 t/ha are have been observed under irrigation in Chile's central valley (G. Edmeades, unpublished data), but this may be a more favourable climate than the US Corn Belt. As one might expect, this is an issue of great interest in the Mid West of the United States of America. 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 t/ha. Higher yields have been observed in contests since 1975 (21-23 t/ha[11]) but the Nebraska number is an average for the period 1983 to 2002. At the other extreme Monsanto, a leading seed company, has set a goal of doubling farm maize yields in the United States of America by 2030 using 2000 yields (8.5 t/ha) as the base, resulting in a FY target of 17 t/ha (www.monsanto.mediaroom.com; Edgerton, 2009); this they will achieve in equal measure through conventional breeding, molecular-aided marker selection and genetic engineering for yield. This is unprecedented breeding progress (2.3 percent exponential, or 3.3 percent linear at the outset, 1.7 percent by 2030), but the issue here is can this be sustained over time, and what would this imply for PY increase to 2030? The PY-FY yield gap in Iowa is currently unclear (Table 4.3), but let's assume a minimum gap of 25 percent: that implies PY will be at least 21 t/ha across the United States of America and somewhat higher in Iowa which currently has a yield 8 percent above the national average. A complication for these projections is the recent paper by Hammer *et al.* (2009) which implies yield and water

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[11] The highest yield reported in the United States of America NCGA Yield Contests in 2007 was 23.9 t/ha (www.ncga.com/files/pdf/2008CYCNationalWinners.pdf). Contest yields (rainfed) in Iowa and Nebraska also show steady yield progress at yield levels about double the state averages.

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 PYw.

6.4 Water-limited potential yield (PY_W)

Equation (3) underlies understanding of PYw 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 the crops' phenological development to the particular rainfed environments, usually meaning selection for earliness whether it is 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[12] and reduces the risk of exhausting available moisture before grain filling (maintaining HI). Secondly PYw progress has derived from spill-over of progress in PY (e.g. higher intrinsic HI if maintained under stress improves yield in both equations (1) and (3) above; also higher RUE may also deliver higher TE). Recent analysis of old versus new maize hybrids shows progress in a dry year in Iowa matches that under wetter potential conditions (Duvick and Cassman, 1999), although they claim that this is spill-over of improved stress tolerance with higher PY not spill-over of yield potential *per se*. Such is the importance of two factors, that attempts to study other factors in PYw variation usually correct this for variation in flowering date and PY (Fischer and Maurer 1978; Bidinger *et al.* 1987), but the picture is not so clear cut in rice, with marked specific adaptation to flooded and to rainfed conditions limiting spill-over to favourable environments.

These other factors in performance under rainfed conditions are potentially numerous, 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 with 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 in this crop (Hammer *et al.*, 2009). Also modest gains in PY_W of wheat has been made by selecting for TE directly (Richards, 2004). But many of the putative drought tolerance traits have not proven useful when used as selection criteria, or carry a significant yield penalty under well-watered conditions.

One area of opportunity derives from the fact that cereals, and especially rice and maize, are sensitive to drought at flowering, when a sharp reduction in the numbers of kernels set can occur (Fischer, 1973; 1985; Bruce *et al.*, 2001), inevitably reducing HI. Maize ovaries starved for carbohydrate grow slowly, and the ability of the ovary to be successfully fertilized can be severely reduced. Pollen is also directly affected by water stress at meiosis in rice and wheat, and carbohydrate starvation doesn't 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 (non-GM) in the sensitivity of grain set in wheat to water stress around meiosis has recently been demonstrated (R. Dolferus, personal comm.).

6.4.1 Water-limited potential yield projections

A variation of equation (3) used in Australia (French and Schultz, 1983) states that $PY_W = k\ (ET - 110)$, where ET is water used in mm and 110mm estimates 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 PYw of wheat for a given level of ET; for example if average ET for wheat in S. Australia is 300mm, then PYw is 3800 kg or 3.8t/ha (c.f., current national average is about 2 t/ha). This approach is an oversimplification but nonetheless has proved a very useful practical guide to PYw in Australia (Fischer 2009). Yield increase through breeding or agronomy can only come from increases in T (for example 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 up may lift PYw by 25 percent (Passioura 2002).

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

Revisiting equation (3), the largest differences in TE are seen between C_4 and C_3 crops, averaging 159 and 83 g biomass/kg 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, though C_4 crops are not necessarily more drought tolerant than C_3 crops (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 PY_W progress of around 100 kg/ha (or 5-8 percent) annually that has been achieved under managed drought stress in the field in tropical maize over a 10 year period, mainly through increases in HI, and this selection methodology is 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 (QTL) adding 47 percent to yield under severe drought (Bernier et al., 2007), and pedigree selection under managed stress showing gains of 4-10 percent per year (Venuprasad *et al.*, 2008). Finally, genetic engineering possibilities abound in the literature and will be discussed later.

6.5 Exploiting heterosis

Heterosis, present in hybrids and obtained by crossing two genetically dissimilar parents, is considered to be a form of stress tolerance, and is often greater for PY_W than for PY. In general hybrids offer around 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 cultivated area globally. 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 outcross, 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, while in wheat technical issues in seed production have prevented any large scale adoption. We predict that this seed yield constraint will be resolved in the next 10-20 years, probably using GM technology, thus permitting hybrids to take over most of the world's rice and wheat area, although we note CIMMYT's lack of optimism on wheat hybrids (Dixon *et al.*, 2008). Thus wheat, rice and maize yields could rise in a one-off yield increase by ten percent, eight percent and five percent, respectively, as the proportion of hybrids under cultivation approaches 100 percent. Because there is an advantage on-farm to growing fresh F1 hybrid seed every year, hybrids foster a viable commercial seed industry and a superior level of intellectual property protection, thereby creating a positive environment for private investment in crop improvement.

6.6 Genetic modification using transgenes

Prospects for augmenting PY by increasing P_{max} and RUE through genetic modification (GM) are currently focused mainly on engineering C_4 photosynthesis into rice and possibly wheat, or of modifying Rubisco and Rubisco activase enzymes or other enzymes close to Rubisco. These are formidable technical challenges. Other promising GM routes to higher PY are claimed, but few have been demonstrated in the field, and often the compensatory response among yield components is overlooked. Engineering better abiotic stress resistance (greater PY_W) may be easier, though 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 *csp* from *Bacillus subtilis* which functions under drought stress as a protein that protects RNA from degradation and for which there is some credible published field plot data (Castiglioni *et al.*, 2008)[13]. 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 six to ten percent under a moisture stress that reduces yields to around 50 percent of the irrigated yield levels (www.monsanto.com). This may mark a major breakthrough for GM breeding targeting abiotic stress and crop yield. Of particular interest is the intent by Monsanto to release this event for use in adapted maize in sub-Saharan Africa on a royalty-free basis through the Water Efficient Maize for Africa (WEMA) Project, in an exciting private-public sharing of cutting edge technology to benefit those who need it the most. Several other recent studies point to possibilities of greater stress tolerance in rice, and rice is the common candidate crop for published work on GM for PY since the genome is sequenced and widely

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

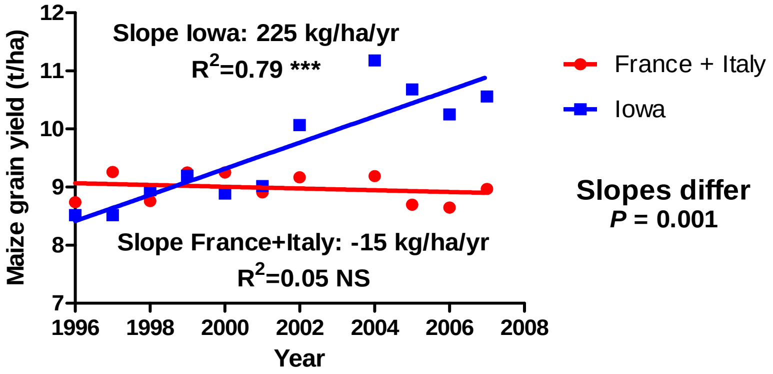
available. However, there are few convincing published reports of yield effects due to transgenes in either wheat or rice (but see Xiao *et al.*, 2009).

Engineering for biotic stress and herbicide resistance has already been hugely successful. It has had a significant environmental effect through reduced pesticide applications, and has lifted yields of crops when 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 corn root worm resistance in maize has improved PY_W where the insect infestation is severe by retaining more roots and increasing water uptake.

Will GM technology be an important contributor to increases in yield in the future? We believe so. The rate of increase in maize yields in the state of Iowa have been significantly greater than that of France plus Italy since 1996, the year transgenic maize was first introduced to farmers' fields (Figure 6.2). 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 unfavorable weather in Europe versus Iowa accounts for all of this difference.

In conclusion, further yield increase via GM for biotic stress resistance and herbicide tolerance is a good possibility; this is yield gap closing. Whether increase will also come from increased PY and PYw *per se* is less 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 consumes around 60 percent of the breeding effort currently at IRRI and in the CIMMYT Wheat Program – a much larger proportion than in maize. This would release considerable additional breeding resources to focus on PY in rice and wheat.

Figure 6.2: Maize yields for 1996-2007 for Iowa and for France + Italy vs. year (The year 2003 is excluded because of severe drought in Europe)



(Source: USDA and FAOSTAT, 2009)

6.7 New tools, efficiency and structures for yield breeding

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

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

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

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

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

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

6.8 Concluding comments: Yield potential toward 2050

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

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

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

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

7. PRICES, EFFICIENCY AND PRODUCTIVITY

Our ultimate concern is not with yields *per se*, but with improving productivity and reducing prices of food staples. Declining real prices of food staples for 1961-2006 at an annual average rate of 1.8 percent for wheat, 2.6 percent for rice and 2.2 percent for maize in world markets has been a major source of poverty reduction, given that food staples make up a large share of expenditures of the world's poor.[14] This decline in

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[14] For a review of evidence see World Bank, 2007.

real prices has been driven by growth in total factor productivity, averaging 1.0 percent globally for all agriculture for the period, 1961-2006, but 1.7 percent for the industrial countries who provide most grain exports (Fuglie, 2008). A distinguishing feature of this period has been that TFP has risen faster than prices have declined, so that both farmers and consumers have benefited (Lipton, 2005).

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

7.1 Prices of non-renewables

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

7.1.1 Fossil fuels

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

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

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

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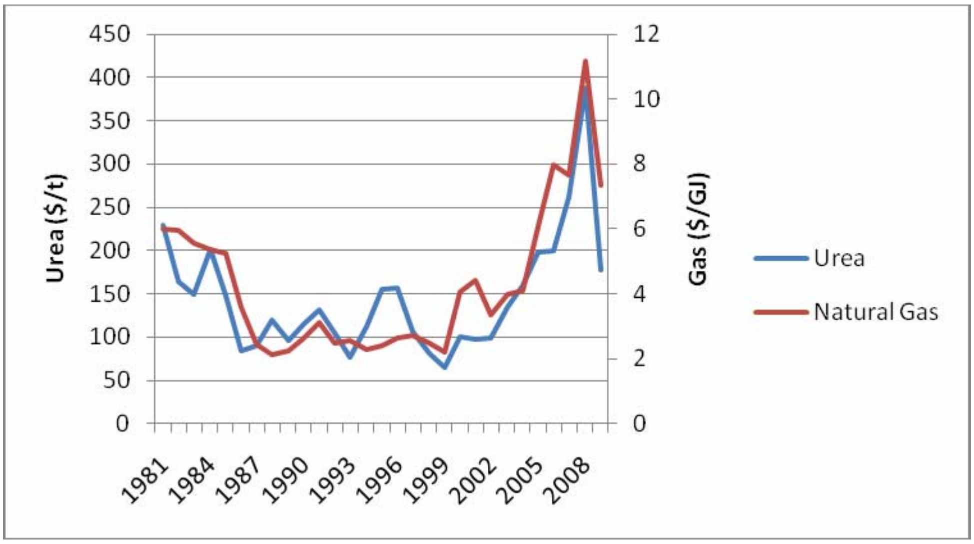
[15] EJ = 10^{18} Joules

[16] GJ = 10^9; 1 litre of diesel contains 38 MJ, 1 ton of maize or wheat about 15 GJ.

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

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

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



Source: World Bank data files

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

Increasing the efficiency of on-farm use of N and the supply of biologically fixed nitrogen are the best options for confronting rising N prices. Numerous studies have documented low on-farm efficiency of applied N, with an average of 33 percent being taken up by the crop, and only 29 percent in developing countries (Raun and Johnson, 1999). Many Chinese farmers may be using N at above optimum levels (Buresh *et al.*, 2004). With better management and lower rates being applied in many cases, N-use efficiency could be improved by 33 percent for irrigated maize to over 100 percent for rainfed rice (Balasubramanian *et al.*, 2004) (Table 7.1). Improvement is already evident in maize in the United States of America for example, where N use per ha has declined through more site-specific application rates, even as yields have increased (Section 4). Precision agriculture provides new tools to further improve efficiency (discussed below). New products such as controlled and slow release fertilizer can also increase efficiency rice (IFDC, 2009). In Bangladesh, over half a million farmers have adopted Urea Super Granules that are deeply placed at planting time enabling N use to be cut by about one third with a corresponding increase in yields of almost 20 percent (IFDC, 2007). Finally, as plant breeding has raised yield, inevitably it has resulted in more efficient N use (Ortiz-Monasterio *et al.*, 1997; Bänziger *et al.*, 1999; Echarte *et al.*, 2008); this is a general principle which applies to most other inputs (e.g phosphorus, water) as well (de Wit, 1992; Fischer, 2009).

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

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

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

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

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

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

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

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

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

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

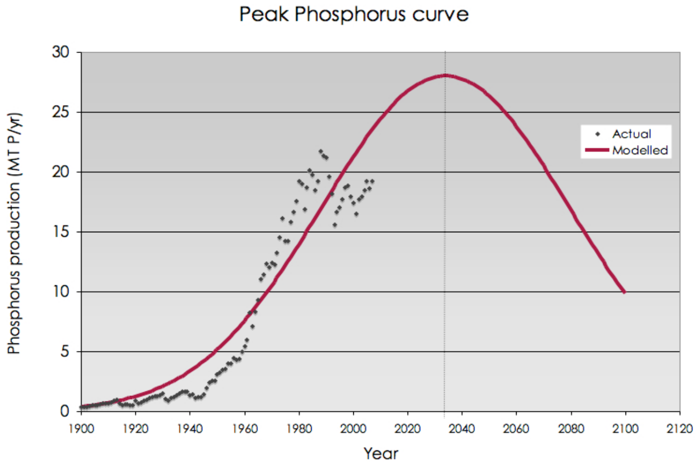
Source: FAO, 2008

7.1.2 Phosphorus

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

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

Figure 7.2: Projection of Peak Global Phosphorus Extraction



Source: Cordell, Drangert and White (2009)

7.2 The Production efficiency gap

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

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

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

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

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

7.3 Agricultural price policies

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

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

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

7.4 Prospects for TFP growth

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

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

Box 7.1: Is TFP Growth Slowing?

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

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

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

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

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

[a] Countries of the former Soviet Union

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

7.5 The key role of R&D investments

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

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

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

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

8. CONCLUSIONS

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

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

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

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

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

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

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

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

Third, many countries face huge challenges in achieving food security, even from a narrow perspective of food supply. We are less concerned about China and India, since they should continue to be largely self sufficient for food needs (although depending on imports for part of their feed needs), but much depends on investments in R&D (below) and management of natural resources. However, there are many countries that do not have the capacity to import large amounts of grain or it would be prohibitively costly to do so, but where population growth is still very high. Most of these are in Africa, but even Pakistan with an estimated

335 m people in 2050 faces a potential food crisis. Climate change will also be a major challenge for many of these countries, adversely affecting yields and diverting R&D resources toward adaptation rather than yield improvement - adding a new dimension to maintenance research.

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

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

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

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