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FOOD SECURITY

# Feeding nine billion: the challenge to sustainable crop production

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In the recent past there was a widespread working assumption in many countries that problems of food production had been solved, and that food security was largely a matter of distribution and access to be achieved principally by open markets. The events of 2008 challenged these assumptions, and made public a much wider debate about the costs of current food production practices to the environment and whether these could be sustained. As in the past 50 years, it is anticipated that future increases in crop production will be achieved largely by increasing yields per unit area rather than by increasing the area of cropped land. However, as yields have increased, so the ratio of photosynthetic energy captured to energy expended in crop production has decreased. This poses a considerable challenge: how to increase yield while simultaneously reducing energy consumption (allied to greenhouse gas emissions) and utilizing resources such as water and phosphate more efficiently.

Given the timeframe in which the increased production has to be realized, most of the increase will need to come from crop genotypes that are being bred now, together with known agronomic and management practices that are currently under-developed.

## The past: increased crop production underpinned by increased yields

Evans (1993, 1998) describes the synergistic effects of the many interacting, innovative technologies that have contributed to past increases in yield. Among the most important of these have been: (i) improved germplasm able to grow vigorously (e.g. hybrids), resist pathogens, and respond to fertilizers without lodging (use of dwarfing and semi-dwarfing genes); (ii) the application of fertilizers and particularly the availability of affordable nitrogen fertilizer; (iii) the development of chemicals to control weeds, pests, and diseases; and (iv) improved irrigation systems, especially in rice-producing countries and for some previously rainfed crops. The consequence of these innovations has been that yields of many crops, especially the major cereal crops maize, rice, and wheat, have increased substantially over the last half century (Fig. 1). Over the period 1961 to 2004, global yield increases for a number of cereal crops have typically been approximately linear (Fig. 1a) with values of 53 kg $ha^{-1}$ $a^{-1}$ for rice, 41 kg $ha^{-1}$ $a^{-1}$ for wheat, and 63 kg $ha^{-1}$ $a^{-1}$ for maize. Increases in yield have also been linear with time in many individual countries [e.g. Scotland in Fig. 1b and see Ewert *et al.* (2005) for wheat yields in several European countries] although, in a few instances, technological innovations resulting in changes in crop husbandry have produced more rapid, stepwise increases in yield [e.g. Australia, Angus (2001); Fig. 1c]. An arithmetic consequence of the linear yield increases with time is that the proportionate increase in yield obtained through breeding programmes has decreased. Of greater concern, though, is that, in some countries and regions, absolute increases in yields are no longer occurring at the same rate despite yields being less than the attainable value. For example, rice yields in SE Asia and wheat yields in the UK over nearly the last decade have been almost constant (Fig. 1d). The reasons for this are complex but probably include almost constant inputs of nitrogen fertilizer to wheat crops in the case of the UK from the mid-1990s onwards (average N fertilizer application was 188 kg $ha^{-1}$ in 2000 and was the same value in 2009; Defra, 2010), and concerns about the long-term availability of mineralized soil N in paddy crops because of the formation of phenolic lignin residues that appear to stabilize soil organic nitrogen (Olk *et al.*, 2006).

It is also noteworthy that, although increased yields have been obtained for many crops in many regions, global increases in production have been confined to a limited range of cereal crops (rice, maize, and wheat) with smaller increases in crops such as potato and soyabean (Godfray *et al.*, 2010). Increased cereal production has supported the increase in chicken and pig production, but also led to concerns that human diets are becoming less diverse. One consequence of this less diverse plant diet has been an increase in the prevalence of mineral deficiency disorders in some humans (White and Broadley, 2009).

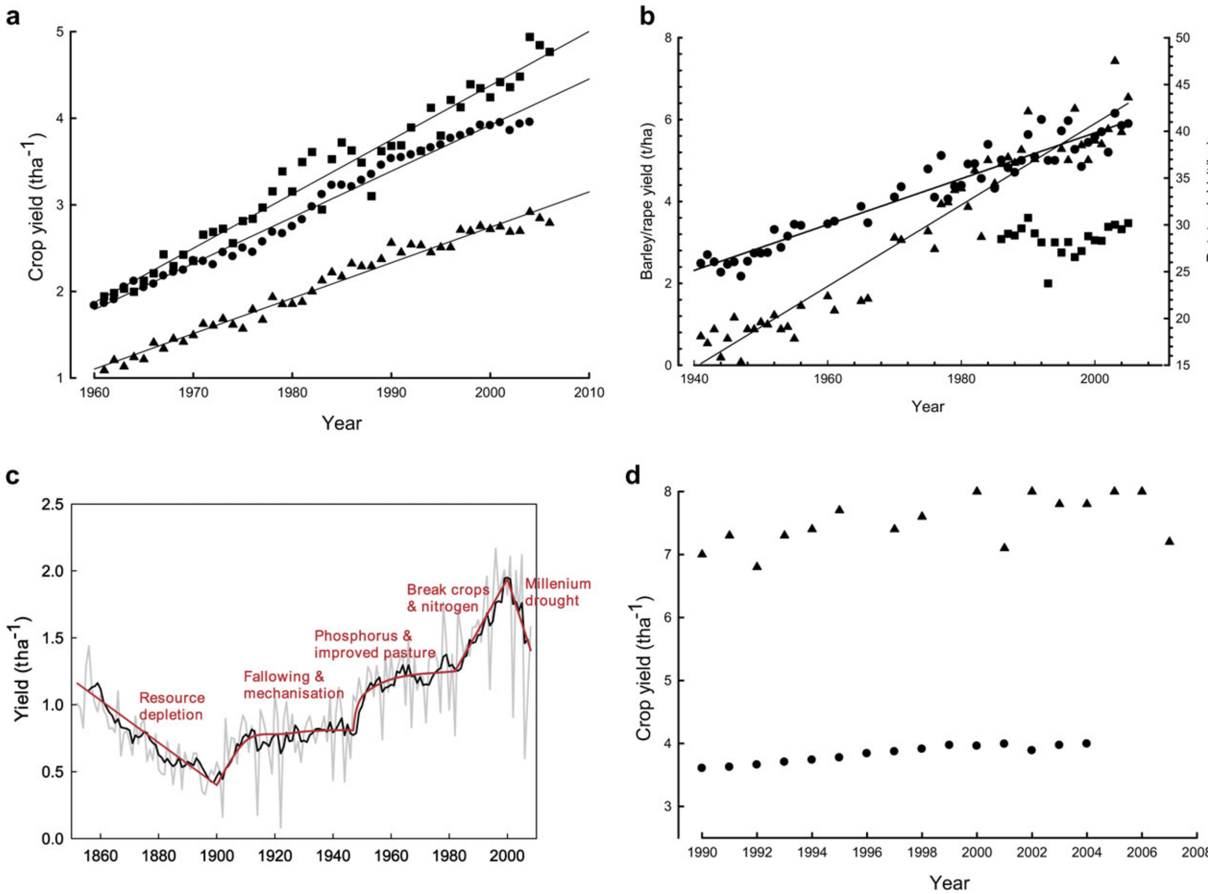


**Fig. 1.** Changes in yields with time. (a) Global average annual yields (data from USDA) for maize (squares), rice (circles), and wheat (triangles); the lines are linear regressions. (b) National average annual yields in Scotland for barley (circles), rape (squares), and potato (triangles); the lines are linear regressions (data from annual farm surveys conducted by Scottish agencies responsible for agriculture). (c) National average annual yield of wheat in Australia (modified from Fig. 4 in Angus, 2001, with kind permission of CSIRO Publishing; http://www.publish.csiro.au/nid/72/paper/EA00141.htm; and personal communication); the dashed line joins annual values, the thin solid line is a 5-year running average, and the solid black line summarizes major trends in yield with respect to changes in crop husbandry. (d) Regional average annual rice yields in Asia (circles, data from USDA) and wheat in UK (triangles, data from Defra).

## The immediate future: reducing yield gaps and producing more with less

Only about 3 billion ha of the world's 13.4 billion hectare land surface is suitable for crop production, and about one-half of this is already cultivated (1.4 billion ha in 2008; Smith *et al.*, 2010). It is widely recognized (Gregory *et al.*, 2002; Bruinsma, 2003) that, globally, only a small proportion of future increases in crop production will come from the cultivation of new land (about 20%) with the majority coming from intensification via increased yield (67%) and higher cropping intensity (12%; Table 1). This means that *per capita* arable land area will continue to decrease (it decreased from 0.415 ha in 1961 to 0.214 ha in 2007) while average cereal yield will need to increase by about 25% from 3.23 t $ha^{-1}$ in 2005/07 to 4.34 t $ha^{-1}$ in 2030 (Smith *et al.*, 2010; Bruinsma, 2009).

Growing crops for biofuels has been highlighted as a potential competitor for land with food crops. It is noteworthy, though, that the area occupied by biofuels and their by-products in 2004 was only 14 Mha compared with 1500 Mha of crops (i.e. about 1% of the total cropped area) and 4500 Mha of pastures worldwide (IEA, 2006). While the reasons for growing crops for biofuels are complex (including increased energy security, increased supplies of transportation fuels, and decreased net emissions of greenhouse gases), the use of land for them is likely to increase (FAO, 2008, gives some projections), and the emergence of biofuels as a new source of demand for agricultural

**Table 1.** Projected contributions (%) to increased crop production between 1997/99 and 2030 (derived from Bruinsma, 2003)

| | Land area expansion | Increase in cropping intensity | Yield increase |
|---|---|---|---|
| All developing countries | 21 | 12 | 67 |
| Sub-Saharan Africa | 27 | 12 | 61 |
| Near East/North Africa | 13 | 19 | 68 |
| Latin America and Caribbean | 33 | 21 | 46 |
| South Asia | 6 | 13 | 81 |
| East Asia | 5 | 14 | 81 |

commodities may assist in the revitalization of agriculture in developing countries with positive benefits for personal livelihoods and economic growth (Pingali *et al.*, 2008).

Reducing the gap between current yields and potential yields is a major goal for the future (Jaggard *et al.*, 2010). In many irrigated cereal systems, yield appears to plateau at or about 80% of potential yield while, in rainfed systems, average yields are commonly 50% or less of potential (Lobell *et al.*, 2009). While part of the yield gap is inevitable because of crop losses during harvest, storage, and transport, and the way that land areas are reported (Jaggard *et al.*, 2010), there are still large differences in performance between adjoining farms. Lobell *et al.* (2009) concluded that a fundamental constraint in irrigated systems was uncertainty in growing season weather; this is also a factor in rainfed systems where interactions between water and nutrient availability are complex (Cooper *et al.*, 1987). In a global analysis of wheat, maize, and rice production, Neumann *et al.* (2010) found that yield gaps were significantly correlated with irrigation, market accessibility and influence, availability of agricultural labour, and slope; the contribution of these factors varied substantially between regions.

So, can the projected crop yields required to sustain a population of nine billion be achieved and sustained? Even in countries with technologically advanced agriculture, it is not inevitable that yields will increase as the data for oilseed rape in Scotland demonstrate (Fig. 1b). The last two decades have seen reductions in investment for crop research in the public sector but a greater role for commercial research especially in the areas of GM and biotechnology. This combination has weakened the public sector and fostered research 'on problems suitable for industrial appropriation, not necessarily those most urgently in need of understanding or solution' (Evans, 1998). The synergistic solutions that emerged from a range of intellectual inputs in earlier decades may be less assured in the immediate future.

## The longer-term future: improving the efficiency of resource use and transformative practices

A primary requirement for the future is to produce higher yields with inputs that do not lead to environmental problems either on- or off-site. Nutrient additions that are inadequate relative to crop offtake degrade land through nutrient mining, while additions that are excessive degrade land, water, and air through leaching, eutrophication, and gaseous emissions (Vitousek *et al.*, 2009). Ideally nutrient additions (whether as mineral fertilizers or manures) and soil biota should be managed to deliver nutrients to crops synchronously with demand (Myers *et al.*, 1994) but this has proved difficult to achieve in practice because applications must be made before the demand exists and large canopies do not permit the application of solid sources to soils. A wide range of decision support tools are available to farmers in the developed world to assist them estimate the demand for fertilizer and manure application rates, and foliar applications of some minerals (especially the less phyto-available ones in soil such as zinc) can be incorporated into insecticide and herbicide spraying programmes; much remains to be done, though, in much of Asia and Africa to improve the advice available.

## Use of fossil energy

In addition to improving the efficiency with which crops use nutrients and water, another key requirement is to increase the amount of solar energy harvested per unit of fossil energy expended. Concerns about the amount of fossil fuel energy expended in crop production and food processing are not new (Pimental *et al.*, 1973; Spedding and Walsingham, 1976), but have recently come to the fore again as energy costs have increased and concerns about $CO_2$ emissions and the need to develop low carbon cropping practices have emerged. Pimental and Pimental (2008) provide a variety of examples to illustrate the poor energy returns of many crop production practices ranging from maize production in Mexico using human power and an axe and hoe returning 10.7 times as much energy as consumed in production to a return of only 2.2 times for rice production in the USA (Table 2). In the Mexican example, the only fossil fuel used was in the production of metal for the axe and hoe; unfortunately the yield (1.94 t ha$^{-1}$) is well below that required to sustain the current and projected future global population. These figures omit the energy required to convert the grains into human food—negligible in the Mexican example but substantial enough in the case

**Table 2.** Some examples of energy use in grain and legume production (derived from Pimental and Pimental, 2008)

| Crop | Country | Tillage | Yield (t ha$^{-1}$) | Inputs (kJ×10$^3$ ha$^{-1}$) | Output (kJ×10$^3$ ha$^{-1}$) | Energy ratio |
|---|---|---|---|---|---|---|
| Groundnut | Thailand | Buffalo | 1.28 | 8 048 | 20 892 | 2.60 |
| Groundnut | USA | Mechanized | 3.72 | 45 817 | 64 051 | 1.40 |
| Maize | Mexico | Human | 1.94 | 2 687 | 28 ,881 | 10.7 |
| Maize | Mexico | Oxen | 0.94 | 3 222 | 13 982 | 4.34 |
| Maize | USA | Mechanized | 8.66 | 33 961 | 130 396 | 3.84 |
| Rice | Borneo | Human | 2.02 | 4 327 | 30 626 | 7.08 |
| Rice | Philippines | Carabou | 1.65 | 7 638 | 25 126 | 3.29 |
| Rice | Japan | Mechanized | 6.33 | 34 405 | 96 163 | 2.80 |
| Rice | USA | Mechanized | 7.37 | 49 542 | 110 995 | 2.24 |
| Soybean | USA | Mechanized | 2.67 | 12 609 | 40 197 | 3.19 |
| Wheat | USA | Mechanized | 2.67 | 17 740 | 35 354 | 2.13 |

of the USA to render the overall energy return close to unity. The energy required to produce N fertilizers is substantial (typically about 60 MJ $kg^{-1}$ N) so one of the most effective means of improving energy efficiency in cropping systems is to introduce legumes into the rotation, although this may also reduce energy output (Hoeppner *et al.*, 2005).

## P-use efficiency

Breeding crops that acquire and/or use P more efficiently is one strategy to reduce the use of P fertilizers. Such crops could produce comparable yields with lower inputs of inorganic P fertilizers or have reduced physiological P requirements and tissue P concentrations, thus reducing the amount of P removed by the crop and, thereby, the amount of P needed to maintain the availability of inorganic P (Pi) in the soil. New varieties can be bred conventionally, based on trait-focused screens of germplasm collections.

A great deal of information is now available about how plants regulate P homeostasis and acquisition from the soil, particularly at the genetic level (Fig. 2; Hammond and White, 2008; White and Hammond, 2008; Lin *et al.*, 2009). Plants appear to have two main strategies to cope with P deficiency in soils. Firstly, there are conservation strategies, by which plants adapt physiologically to their native Pi supply and conserve what they have by either producing biomass more efficiently (e.g. replacement of phospholipids) or reducing growth (e.g. reduced photosynthesis) (Fig. 2). Secondly, there are active strategies, which tend to occur below ground and include (i) actively increasing access to the deficient resource by exploring more soil and (ii) actively altering the rhizosphere environment to increase the supply of Pi to the root. These active strategies have been demonstrated to be regulated by both sucrose and phosphate signalling pathways (Fig. 2). The physiological state of a P-deficient plant is quite specific and the response is multigenic in nature with, for example, over 1000 genes being differentially regulated under these conditions in *Arabidopsis* (Hammond *et al.*, 2003; Morcuende *et al.*, 2007). Under conditions of P-starvation, plants have an increased root/shoot biomass ratio (Lynch, 1995), an alteration of root architecture (Williamson *et al.*, 2001; Lopez-Buccio *et al.*, 2000), and many more lateral roots and long root hairs (Bates and Lynch, 1996; Fig. 2). Also high affinity P transporters are more abundant (Mudge *et al.*, 2002; Smith *et al.*, 2003) and organic acids and phosphatases are being synthesized and secreted (Li *et al.*, 2002; Fig. 2).

Mutants with allelic variation and/or altered expression of genes affecting P acquisition or P use within the plant have been generated. Several of these mutants illustrate strategies for developing crop plants that acquire and/or use P more efficiently. Mutations that improve P acquisition from the soil could improve crop growth when P availability in the soil is poor. Transgenic plants that secrete microbial phytases into the rhizosphere have the potential

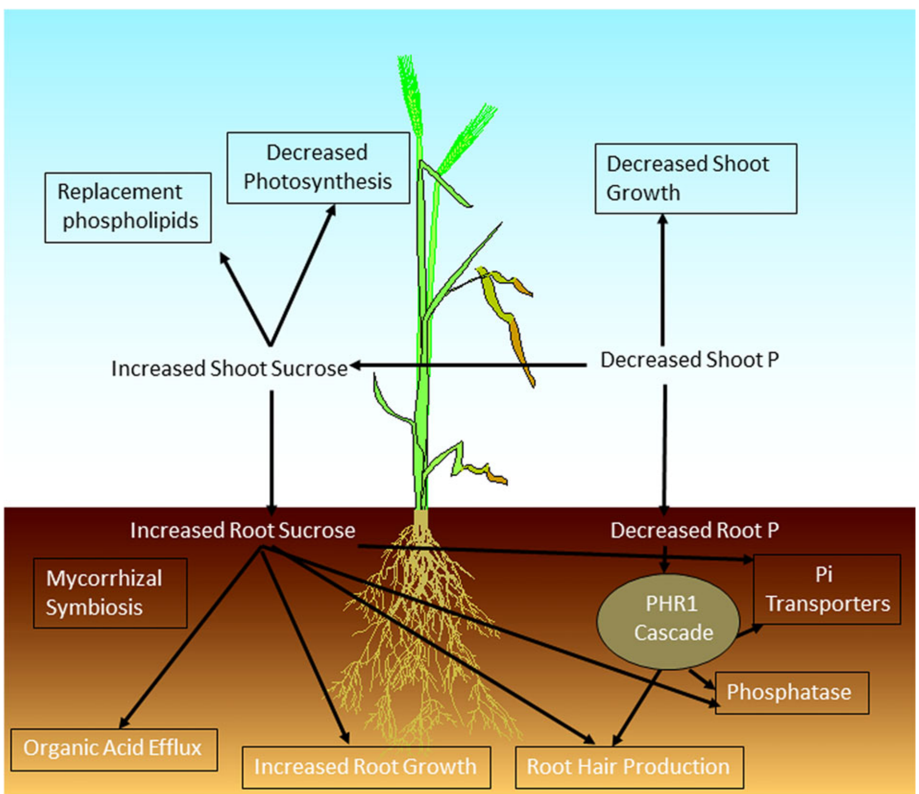


**Fig. 2.** Regulatory networks co-ordinating plant responses to variations in P supply. (White and Hammond, 2008) with particular reference to PHR1-mediated acclimatory responses to P-starvation. Arrows indicate positive regulation.

to release P from inositol phosphates and show enhanced growth and P nutrition when inositol hexaphosphate is the major source of P (Richardson *et al.*, 2001; George *et al.*, 2004, 2005*a*). However, when grown in most soils these plants have comparable growth and P nutrition to control plants (George *et al.*, 2004, 2005*b*). Similarly, over-expression of a bacterial citrate synthase gene in tobacco has been reported to increase citrate efflux from roots and to increase the availability of P from Ca-P (López-Bucio *et al.*, 2000), but an effect on plant growth and P acquisition is not always observed (Delhaize *et al.*, 2001). The expression of a wheat malate transporter gene (ALMT1) in barley has been shown to be effective in increasing P uptake by transgenic plants, but only in severely acidic soil conditions (Delhaize *et al.*, 2009).

Mutations altering root morphology also have the potential to enable plants to acquire more P. For example, barley genotypes with long root hairs have higher yields than genotypes with no root hairs on soils with low P availability (Gahoonia and Nielsen, 2004; Brown *et al.*, 2011), and genotypes of bean, maize, and brassicas with larger root systems have better growth under P-limiting conditions (Rubio *et al.*, 2003; Liu *et al.*, 2004; Hammond *et al.*, 2009). The differential expression of a number of transcription factors and genes has resulted in greater accumulation of P in plants (Bari *et al.*, 2006; Chiou *et al.*, 2006). A T-DNA insertional knockout of a specific *Arabidopsis* gene (*AtSIZ1*) caused exaggerated Pi starvation responses, including the cessation of primary root growth, extensive lateral root and root hair development, an increase in the root/shoot biomass quotient, and greater anthocyanin accumulation, even though intracellular Pi concentrations in *siz1* plants were similar to the wild type. Many of these mutants exhibit constitutive P-deficiency symptoms, including increased P uptake, which might be beneficial in some agricultural systems. Mutations that improve crop growth when soil P availability is low, through better physiological utilization of P, may also be useful in breeding crops for reduced P inputs. For example, OsPTF1, a bHLH transcription factor from rice, whose expression increases in the roots of P-starved plants, has been shown to enhance tolerance to P-starvation (Yi *et al.*, 2005). Overall, we appear to be on the cusp of being able to deploy a number of post-genomic tools to crop germplasm that will allow them better access to P resources. However, such developments will not replace completely the need for applications of P fertilizers, and genetic improvements in crops must go hand-in-hand with increased efficiency in the use of current stocks of P and the identification of alternative sources of P for crop production.

## Concluding remarks

The increasing future demand for crops will continue to be met largely by increasing yields. Cereal yields and production have increased 3-fold in the last 50 years and will need to continue to increase at the same absolute rate for the next 40 years. As in the past, multiple approaches will be required with an immediate effort required to understand yield gaps and how that might be reduced in specific regions and farms. As potential yields are approached more closely, the concomitant requirement to use all resources more efficiently will pose a considerable challenge.

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