Crop yields and food security: will yield increases continue to feed the world?

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Abstract
In the last 20 years, rates of farm yield (FY) progress have slowed, falling below 1 % per annum in most situations for most crops, with the notable exceptions of maize, cassava, sugar beet, canola and oil palm. Estimates suggest we need at least 1.25% yield growth to ensure food security to 2050. For various crop situations, potential yield (PY referring to the absence of stresses), or water-limited potential yield (PY_w in the absence of stresses apart from limited water), are estimated largely from trial results with the latest varieties. This can be compared to FY in the same situation, and the yield gap (PY-FY as % FY) calculated. FY progresses through increasing PY and closing yield gaps. Progress in PY and PY_w, as determined largely by breeding, is generally below 1% for all crops in all situations studied. New agronomy, often interacting positively with new varieties, can also drive PY progress but there is little in sight. Breeding for yield remains important for the future, even as biological limits to yield must be approaching. However we don't believe genetic engineering will directly accelerate PY progress, at least in the next 30 years or so, though molecular tools will speed conventional selection gains; however PY progress > 1% seems unlikely. Thus yield gap closing becomes vital if the extra crop area to feed the world is to be kept to a minimum (< +100 Mha). Current yield gaps range from 20% to 440%, with obvious effects of crop, environment, and stage of national economic development. Advanced well-watered cropping situations like wheat in the UK or maize in Iowa are already showing yield gaps little more than the economic minimum of around 30%, but there are many other situations where the yield gaps look highly exploitable. Breeding and agronomic research both have roles to play, as does improvement in infrastructure, communications and IT, institutions and policies in many developing countries. All these areas will require boosted investment if gap closing, normally quite slow, is to be lifted sufficiently to bring annual FY progress up to 1.25%.

Key words
World food security, yield progress, wheat, rice, maize, soybean

Introduction

World grain price spikes since 2007 have stimulated great interest in world food security. Many conclude that the world's future food supply is far from secure. Analyses follow familiar paths, full of uncertainties and assumptions on both the demand and supply sides. In this short paper we wish to update and extend in summary form the views on this topic introduced at the last Agronomy Conference (Edmeades et al. 2010) and soon to be published in a book (Fischer et al 2012).

Both the projection for world population to 2050 (7.9 billion to 10.1 b, mid-range 9.3 b, up 31% from 2011) and that for per capita income annual growth (0.9% to 3.2%, mid-range 2.5%) have wide ranges (Nelson et al. 2010). Food consumption as a function of per capita income is less uncertain, with a fairly predictable shift from coarse grains and rice to vegetable oils, sugar, fruits, vegetables, and animal products. Estimates for biofuel are also uncertain, with grain to biofuel ranging from 100 Mt to 450 Mt by 2050. Finally demand is sensitive to price, and we have to look to computable equilibrium modelling for a balancing price. Commonly modellers focus on cereal prices since cereals are more than half world (food plus feed) calories. Models put 2050 cereal demand (food plus feed plus biofuel) at from 3000 to 3650 Mt (e.g. Nelson et al. 2010; Bruinsma 2011; Fischer 2011)). If we assume its 3500 Mt, 41% above 2010 cereal production, it could be met by a linear increase starting at 1% p.a of torads production. It should be noted that the agricultural production in value terms will have to grow faster (Bruinsma, 2011), maybe 40% faster (i.e. 1.4% p.a.), because of the shift in demand to higher value products. This may not affect the underprivileged so much, but also all equilibrium models predict increases in real prices relative to the historic lows which prevailed from 2000-2005 (+30% in IIASA modelling, Fischer, 2011), which is bad for the poor. We conclude therefore that 1% annual growth in crop production is not enough, and we ought to aim for 1.5%, meaning an increase in supply of 60% 2010 to 2050.

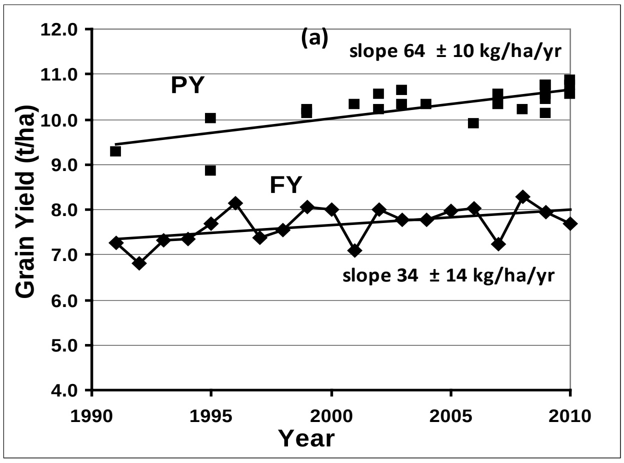
On the supply side there are just as many uncertainties, including arable land area, cropping intensity (crops per year), crop yield growth, and again price effects. In the 50 years to 2010, crop harvested area grew about 30%, but the major contribution (70%) to meeting demand growth was yield increase, even as real prices fell steadily for the first 45 years. This paper questions whether future supply can continue to grow along these same lines, largely by yield growth, and whether it can grow rapidly enough to meet the demand projections with minimal real price increases.

World crop area prospects

We cannot ignore increase in crop area in this discussion. It has been slow since 1960 (total increase of 28%, FAOSTAT), approximately divided between an increase in arable area (used for temporary crops, currently 1400 Mha) and an increase in cropping intensity (currently 90%). Bruinsma (2011) predicts a further increase to 2050 (10%), arising from a small increase in net arable area (3%) and an ongoing increase in cropping intensity (7%). Contrary to popular belief, there is considerable cleared but uncropped fallow land with good cropping potential in sub-Saharan Africa, Latin America and Russia. On an annual basis today, the 10% increase in area amounts to cropping area growth of 0.25% per annum, thereby lowering the needed yield increase to 1.25%. The small increase in the proportion of irrigated crops that is predicted (from 23% to 24%, Bruinsma, 2011) is not however enough to significantly impact on yield growth.

Crop yield prospects: approach

We define the potential yield (PY) of a crop in a region as the yield of the most recent variety in the absence of manageable abiotic and biotic stresses, but grown under the natural resource base (climate, soil) representative of the region. We also define a water-limited PY (PY_w) for rainfed regions. Actual yield of the region is farm yield (FY) and it is global farm yield which needs to grow at 1.25%. It is useful to separate FY growth into two components (1) PY increase and (2) closing of the gap between PY and FY. This is illustrated for the last two decades in Fig 1(a) for winter wheat in the UK, a well watered environment which is summarized as follows: PY progress at 64 kg/ha.yr or 0.6% of the current PY of 10.7 t/ha, FY progress at 34 kg/ha.yr or 0.2% of the current FY level of 8 t/ha. Thus the yield gap (always as a % of FY) is 34% and fairly steady. Fig 1(b) shows the situation in the rainfed wheat region of south western Western Australia: PY is progressing at 0.5% and currently stands at 2.6 t/ha, FY is progressing faster (1.0%) and is presently 1.8 t/ha, making a yield gap of 44% of FY.



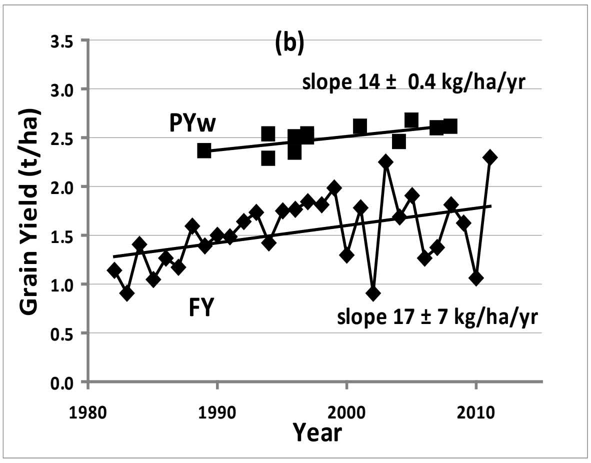


Figure 1. Change in potential yield (PY, PY_w) and farm yield (FY) of wheat in the (a) UK and in (b) Western Australia since 1980; PY, PY_w plotted against year of variety release. Source PY from HGCA trials (www.hgca.com/content.template/23/0/varieties , PYw from National Variety Trials (www.nvtonline.com.au , UK FY from FAOSTAT, WA FY from ABARES.

Crop yield progress in wheat, rice, maize, soybean.

A similar analysis to that in Fig 1 was carried out for many wheat growing regions of the world and a great deal can be said about the agronomic innovations, breeding progress and FY constraints in each case, but space here permits only a summary (Table 1). Suffice to say that average FY progress was close to the global average (0.9%), but that average PY growth was only 0.5%, and this is largely due to genetic improvement. Yield gaps averaged 50% (range 30-75%) and gap closing was not very evident. In this respect WA in Fig 1(b) was an exception. Gap closing is largely due to improved crop management.

Table 1 Summary of recent farm yield (FY) and potential yield (PY) growth over the last 20 years, their current levels and the yield gap as a % of FY, arranged by wheat megaenvironments (MEs). Estimates from Fischer et al. (forthcoming book).

ME	Region	Rate of progress (%)		Predicted yield (t/ha) and gap (%), in 2009 or 2010			Comment on gap
		FY	PY	FY	PY	Gap	
1	YaquiValley, Mex	0.4	0.3	6.0	9.0	50	steady
1	Punjab, India	0.7	0.2	4.5	7.0	55	steady
1	Jiangsu, China	0.8	0.7	4.6	7.5	65	steady
4	W. Australia[a]	1.4	0.5	1.8	2.6	45	closing
6	Saskatchewan[a]	0.8	0.6	2.3	3.8	75	steady
6	Saskatchewan[a, b]	0.7	0.5	2.2	3.6	65	steady
6	N.Dakota[a]	1.0	0.7	2.5	4.0	60	steady
6	Finland	1.0	0.8	3.7	4.8	30	variable
10	Shandong/Henan	1.7	0.6	5.8	8.8	50	closing
11	United Kingdom	0.4	0.6	8.0	10.7	35	steady
12	Kansas[a]	0.7	0.3	2.8	3.8	35	steady
	Unweighted average	0.87	0.53	4.0	6.0	51	

a. These are rainfed cropping regions commonly with water shortage so PY_w was being estimated. b. Durum wheat.

Similar analyses have been carried out on key maize, rice and soybean regions (Table 2). Rice gave higher FY and FY progress than the world rice average (because of the regions included in the sample) but again PY progress was low (0.5%); gaps were more variable than wheat, with high gaps in rainfed systems in Asia. Maize FY and FY progress in the sample was close to the world average, with PY progress notably higher than rice and wheat. Maize yield gaps were frequently large (100-200%, China, Ghana and Brazil) or very large (440% East Africa); in contrast FY, PY and gap in Iowa, the most advanced maize growing region, were 11t/ha, 16 t/ha and 44%, respectively. The sample of soybean regions showed faster FY progress than the whole world (1.5 vs 1.0%), but again PY progress was low (0.6%); yield gaps were all uniformly narrow (35%). Larger gaps in rice and maize were found in developing country rainfed situations. Other crops were analysed (cassava, oil palm, sugarcane, pulses, potato) but their impact on global food is small.

Table 2 Average farm yield (FY) and potential yield (PY) growth over the last 20 years, their current average levels and the average yield gap as a % of FY for all the case studies with rice, maize and soybean.

Crop	Rate of change (%)		Predicted yield (t/ha), and average gap (%), in 2009 or 2010			Range of gaps (%)
	FY	PY	FY	PY	Gap	
Rice (10 regions)	1.15	0.46	5.2	8.4	79	20–150
Maize (6 regions)	1.62	1.12	5.1	11.7	190	44-430
Soybean (3 regions)	1.53	0.6	2.6	3.4	35	35-35

Yield prospects

Perhaps the most notable result is that PY progress in wheat, rice and soybean has slowed to around 0.5% p.a. (claims of much higher rates seem to always fail under careful scrutiny). In the past this progress was greater, coming from both genetic improvement and increased agronomic inputs with which new varieties interacted positively (e.g. increased N and earlier planting in the case of most crops, increased density as well in the case of maize). It is hard to see further PY advance through agronomic improvement, but that through genetic improvement should continue at the 0.5% rate. Maize is the exception, still showing just over 1% PY progress, perhaps because it is targeted by huge private sector investments around the globe and has less quality and disease challenges for the breeders. PY progress is getting harder in all cases, but new tools such as marker-aided and whole genome selection, as well as private sector involvement, will help. Despite slowing yield growth, there are no signs of PY limits being reached: reasonable physiological considerations (e.g. radiation and water use efficiency, harvest index) still provide headroom for progress, and much genetic variation remains untried. However it is becoming increasingly doubtful that genetic engineering will directly lift PY in the next 30 or more years. Climate change will start to impact more strongly especially through warming, but there is a large untapped scope for genetic adaptation, as well as for agronomic adjustments which are taking place continuously. As a result we do not expect it to have a large effect on gains in PY or FY to 2050.

Closing the yield gap is the other route for lifting FY, and probably the most important for the next 40 years. Because of economic reasons the minimum PY-FY gap is likely to be about 30%. But many situations especially rainfed Asia and Sub-Saharan Africa have gaps greater that 100%, and there are a number in the range 40-100%, like wheat in Australia. Speaking generally breeding and agronomic research continue to have major roles in yield gap closing. For example Bt-crops have lifted FY because there is less insect damage at the farm level than before, and zero till has meant a lower proportion of crops are sown too late. GM-derived disease resistance is likely in the next decade and will reduce disease losses and speed breeding. Fine tuning all these things can close the gap in advanced nations, and should happen. Where gaps exceed 100%, additional constraints, mostly off the farm, hold back FY: these include high input and low output prices due to poor roads and markets, weak institutions like uncertain land ownership, expensive credit, lack of law enforcement, plus poor rural education and health This is the predominant scenario in Sub-Saharan Africa, but there are some recent successes which reinforce the gradual move towards a consensus and action on the way forward there and in rainfed Asia. Huge investments however are needed in infrastructure and services as well as R, D and E, and also critical are proper policies for agriculture.

Sustainable intensification of cropping.

Gap closing is essentially the sustainable intensification of cropping, which embraces increased cropping intensity and particularly increased crop yield, so as to minimize the expansion in arable area and the associated high green house gas (GHG) emissions (Tilman et al. 2011). In many places the use of external inputs must increase, but fortunately increased yields through improved varieties and greater nutrient and water inputs, if managed properly, can lead to more efficient use of resources (i.e. less N, P, water, energy, GHG per unit product). Mostly it is a question of inputs meeting but not exceeding crop demand or needs, especially critical with N fertilization designed to minimize gaseous losses. Lowering methane emissions from paddy rice however remains a special challenge. Again much R and D is needed, and on-farm management has to become much more sophisticated especially where gaps are large

Conclusion

World food security demands to 2050 linear annual yield growth of at least 1.25% p.a. relative to 2010 yield. Prospects for lifting yield growth to this level depend on (1) lifting the rate of PY (or PY_w) progress and/or (2) closing the FY to PY yield gap. Many possible routes are discussed for raising PY breeding progress from the current levels of about 0.5% p.a., but none seem very likely. On the other hand yield gaps often exceed the usual minimum of 30% of FY, and many exceed 100%, offering many possibilities of gap closing with existing technologies, aided by more robust varieties and smarter agronomy. Where gaps are large in developing countries, off-farm developments will also be essential, involving major investments in rural infrastructure and institutions. In all situations more research, development and extension investment is essential if we are to intensify cropping enough and in a sustainable manner to reach the above goals.

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