Stocktake on cropping and crop science for a diverse planet.

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Abstract
The paper begins by examining recent progress in yield and area of the major world crops, and the general underlying technologies which have driven this progress. But despite these successes of crop science, yield growth rates have now fallen to levels below those needed to both substantially alleviate the remaining serious malnutrition and poverty in the developing world and as well as to protect non-cropped areas. Slowing farm yield growth appears to be related to slowing yield potential progress in major crops, at least in percentage terms, and to persistent yield gaps in less well endowed cropping areas where the adoption of better technology has never been strong and new extension paradigms are being attempted. Besides over all cropping environments the natural resource base must be maintained or, more often, restored. All of this represents a huge challenge for crop science, and for politicians and policy makers whose increased investments in rural infrastructure and institutions are also a necessary component of the progress to which we all aspire. On top of this we are currently faced with the special challenges represented by uncertainty surrounding GMOs, by inevitable but poorly predictable climate change, and by perceived inequity in access to the essential intellectual property necessary for crop research. This paper can only touch upon these critical issues; the subsequent Congress will examine them and others in depth.

1. Introduction

Humankind is totally dependent on crops for most of our food and feed, as well as for many other important plant materials, and will remain so for the foreseeable future. Currently crops occupy nearly one fifth of the earth's vegetated surface, and involve more of the world's workers than any other enterprise, a massive human endeavour of great moment.

This paper begins optimistically, with a quick look across crops at the impressive gains made in production, largely through yield increase, in the last 40 years by the efforts of crop scientists and farmers together. Some of the major scientific discoveries behind these gains, and often embracing several or all crops, are then touched upon. But yield progress is slowing significantly and this issue, of concern to all involved, is discussed. Besides several of the other substantial challenges currently facing cropping are outlined.

2. Growth in area, yield and production across crops.

About 1950, global arable area increase slowed markedly, while crop yield increase accelerated and kept pace with or even got ahead of population growth. Supply exceeded demand, driving down real prices of crop products such as grains, and boosting average per capita food production and rural wealth, particularly in Asia (Asian Development Bank 2000). While demand factors, like population and per capita income increase, and distributional ones, like trade, are very important in all of this, they will be discussed in other papers in the Congress, and this paper will focus on the supply side of cropping. This is done by disaggregating the global crop area and yield changes for the 40 year period from 1961-3 to 2001-03 into the key component crops and by developing and developed country categories (Tables 1,2,3; which use FAO statistics and the FAO definition of developed countries which has always included USSR and/or exUSSR countries).

Table 1 shows the key cereals. For the major three, wheat, rice and maize, the source of 70% of our calories, there is some area increase in developing countries (around 1% pa), which is associated more with increased cropping intensity, often linked to spreading irrigation in Asia, than with expanded arable area. But it is yield growth (at 1.9 to 2.8% pa) which dominates, exceeding rates for the same crops in developed countries, and in the case of wheat and maize, lifting developing country production up to close to that of developed ones. None of the other cereals compare in size to the big three, and indeed they have usually shrunk in area, while growing only modestly in yield, such that their production growth (approximately the sum of area growth and yield growth) has been very slow, with the exception of barley in the developed world, where animal feeding and beer making are probably key demand factors driving this.

Table 1. Developing and developed country production and yield of cereals in 2001-2003, and area and yield growth since 1961-1963 (% pa, compound).

Crop	Category	Production 2001-03 million m t	Change over period 1961-3 to 2001-3 Area % pa	Yield % pa	Yield 2001-03 kg/ha
Wheat	Developing	264	0.7	2.8	2653
	Developed	309	-0.4	1.9	2724
Rice	Developing	561	0.9	1.9	3812
(paddy)	Developed	25	-0.4	0.7	6462
Maize	Developing	282	1.1	2.4	3034
	Developed	337	0.1	2.2	7128
Barley	Developing	25	-0.8	1.3	1674
	Developed	116	0.2	1.3	2812
Sorghum	Developing	44	-0.1	1.0	1109
	Developed	14	-0.7	0.6	3255
Millet	Developing	26	-0.3	0.7	763
	Developed	Negligible			

Table 2 shows the key non-cereal grain crops. Soybean has reached the status of a major world crop, having grown massively in area, particularly in Brazil, Argentina and India, and also in yield, such that developing country production now greatly exceeds that in developed countries. At the same time, ground nuts and especially pulses have languished. However rapeseed, although still a small crop globally, presents another spectacular growth story, both in developing and developed countries.

Table 2. Developing and developed country production and yield of key non-cereal grains in 2001-2003, and area and yield growth since 1961-1963 (% pa, compound)

Crop	Category	Production 2001-03 million m t	Change over period 1961-3 to 2001-3 Area % pa	Yield % pa	Yield 2001-03 kg/ha
Soybeans	Developing	104	3.6	3.0	2173
	Developed	78	2.4	1.1	2444
Pulses	Developing	41	0.4	0.2	675
	Developed	15	-1.4	2.0	1612
Groundnuts	Developing	33	1.0	1.3	1367
	Developed	2	-0.7	2.0	2854
Rapeseed	Developing	16	2.2	2.8	1288
	Developed	19	6.0	0.8	1897

Table 3 shows the remaining major crops, those often overlooked by grain scientists, but well represented in this Congress. There are some interesting stories. Roots and tubers (without potato), an important staple in the tropics for developing countries, have done modestly well, but nothing like as well as potatoes in developing countries, which is fast overtaking potatoes in the developed world. The big money crops, however, for farmers small and large alike, are the vegetable and fruits: in both cases the developing world, with rapid growth especially in area, has overtaken the developed world, where area is stagnant. There will be more about this later in the Congress. Two other commercial crops, plantation crops in some regions but as well, small holder crops, namely sugar cane and oil palm, have also grown notably, in the case of oil palm in fact quite spectacularly. Finally we see seed cotton (lint plus seed), a small but valuable crop, growing ahead in developing countries, but not doing much in developed ones.

Table 3. Production and yield of key non-grain crops in 2001-2003, and area and yield growth since 1961-1963 (% pa , compound)

Crop	Category	Production 2001-03 million m t	Change over period 1961-3 to 2001-3 Area % pa	Yield % pa	Yield 2001-03 kg/ha
Roots/tubers	Developing	370	0.7	1.1	11,140
(excl potato)	Developed	negligible			
Potatoes	Developing	142	2.5	1.5	15,200
	Developed	172	-1.6	0.8	17,600
Vegetables	Developing	649	2.5	1.7	16,100
(incl melons)	Developed	163	-0.2	1.4	20,600
Fruits	Developing	354	2.7	0.7	9,500
	Developed	123	0.1	0.8	10,300
Sugar cane	Developing	1227	2.0	0.8	64,900
	Developed	88	2.2	-0.3	74,700
Sugar beet	Developed	200	-0.9	1.5	41,500
Oil palm	Developing	136	3.0	2.9	12,130
Seed cotton	Developing	38	0.1	2.2	1,608
	Developed	18	-0.2	0.8	2,095

3. Crop science behind the area and yield changes.

Breeding

Each crop has its own story but for all, breeding has been central to improvement. The social agenda for crop science in the 20th century was set by the Irish Potato famine of the 19th century, while the scientific strategy was shaped by the rediscovery of Mendel's laws of inheritance in 1900. No wonder the early applications of Mendelian genetics were related to breeding crop varieties resistant to diseases and pests, since the desire was to avoid calamities like those caused by *Phytophthora infestans* in potato in the 1840's in Ireland. With opportunities for planned genetic recombination, the search for new genes started. This led to efforts like those of NI Vavilov to identify centres of diversity for major crop plants and to preserve them in *ex-situ* collections. Stability of performance through use of genes for resistance to biotic stresses was given higher priority than productivity improvement, in the early days of Mendelian genetics. But this soon changed, with growing interest in the adaptation, phenological and other, of crops to new environments, in product quality, and in intrinsic yielding ability, and with better tools to guide selection for these largely quantitative traits.

The 20th century later witnessed the introduction of several new breeding techniques for enhancing the productivity, profitability, sustainability and stability of major cropping systems. These included the exploitation of hybrid vigour, chromosome doubling through colchicine treatment, polyploidy, aneuploidy and genome breeding, induction of mutations through ionizing radiations and chemical mutagens, wide crossing, embryo and anther culture techniques and finally the onset of the era of molecular genetics following the discovery in 1953 of the double helix structure of DNA, the chemical substance of heredity, by Watson, Crick, Wilkins and Franklin. This led to the development of recombinant DNA technology and thereby to the possibility of moving genes across sexual barriers, and it is no surprise that molecular breeding now occupies a significant part (about 20%) of this Congress.

In wheat, rice, sorghum, and barley, the exploitation of **dwarfing genes**, often single major genes, brought shorter stature, more efficient dry matter partitioning to reproduction, as reflected in higher harvest index, and hence increased yield potential. This development coincided with the advent of cheap nitrogenous fertilizer to which the shorter cultivars were better able to respond, because of their greater efficiency and also because of their greater lodging resistance. These were the varieties of the green revolution in the 1960s in irrigated environments in Asia, and this story has been told many times. It is important to add here that these dwarfing genes have more recently penetrated, in the form of modern cultivars, other less favourable environments (cold, hot, dry, acid soil) in developing and developed countries, with almost equal positive impact on yield. For example in the case of wheat, by 1997, 81% of the developing world was planted to semidwarf wheats, including 92% of South Asia and 89% of South America (Pingali 1999)

But another scientific development which preceded the large scale exploitation of dwarfing genes and of equal moment was the discovery of **heterosis. Hybrid maize** reached US farmers in the early 1930s: grain yield increased spectacularly (heterosis relative to the hybrid yield was around 65%, Duvick (2005)). Absolute heterosis has increased little since then, and relative heterosis has fallen, so the yield jump was essentially a single event, but of course the new maize hybrids were adopted very rapidly in USA and have never looked back. CIMMYT/IITA surveys (Pingali 2001) estimate that in the late 1990s 37% of the developing world's maize area is planted to hybrids (and another 12% to improved OPVs), with temperate areas ahead of nontemperate ones.

Heterosis in rice or **hybrid rice** was a more recent, but nevertheless outstanding, breakthrough, made in China in the 1970s and exploiting cytoplasmic male sterility. Now half of China's rice area (total 30 m ha) is planted to indica hybrids, where they yield 10 to 15% morethan pure line varieties. Elsewhere in subtropical and tropical Asia some 0.8m ha are planted to hybrid rice. In India the yield advantage of hybrids ranged from 1.0 to 1.5 t/ha but adoption is still low. A mixed advantage of hybrid rice is that on the one hand seed production is labour intensive, so that rural labour shares in the benefits of heterosis, but on the other hand, high seed costs currently limit adoption. A huge research effort is now underway to develop new male sterile systems and superior parents in order to better exploit heterosis in rice (see Virmani, Mao and Hardy 2003). Hybrids are also utilized in sunflower, sorghum, and sugar beet, and a little in wheat; more recently hybrids have begun to be exploited in cotton, rapeseed, pigeon pea and millet, but time prevents discussion of this equally exciting crop science.

While dwarfing genes and heterosis have given spectacular one-off yield jumps, we cannot ignore the steady yield progress achieved in most crops through so-called **empirical breeding for yield,** comprising the location of genetic diversity, its hybridization, selection amongst progeny, and finally large scale multilocational yield testing: the result is the steady accumulation of favourable minor genes and gene combinations. It is well illustrated by the huge progress in maize yields since the advent of hybrids. Duvick (2005) thoroughly describes the linear increase in yield of hybrids released between 1930 and 2001 in the mid west of the USA, an increase averaging 77 kg/ha/yr, and cites that hybrids in Brazil have progressed at 123 kg/ha/yr between 1963 and 1993. In the US case, new hybrids have a higher plant density optimum, more erect leaves, smaller tassels, better stay green and higher grain filling dry matter accumulation, and better lodging and stress resistance, but in contrast to other crop improvement, are no shorter, earlier, or markedly higher in harvest index (Duvick, 2004). There has been equally impressive steady breeding progress in Canada and US soybean yields (Specht et al 1999): from the early 1900s until the 1990s, yield has grown at from 10 to 30 kg/ha/yr, with a jump in rate of progress upon the advent of hybridization, as distinct from introduction and selection alone. Again grain filling dry matter accumulation, and lodging and stress resistance have improved. Recently Kawano (2003) has described linear breeding progress in cassava yield in Colombia and S.E.Asia of the order of 2%/yr over several decades: keys to this success were hybridizing to genetic diversity, harvest index selection, and widespread yield testing. Similar recent studies document breeding progress in wheat (Sayre et al, 1998; Brancourt-Hulmel et al 2003) and cotton (Lu et al 1994; Meredith 2000), and more cases will be reported in the Congress. There is no doubt that so-called conventional breeding for yield has been a powerful tool for crop scientists, and that yield has advanced under both optimal conditions as well as many of those with constraints arising from abiotic stresses.

As mentioned earlier, host plant resistance to pests and diseases has been a major goal of breeders and is a notable achievement in most crops, especially the cereals. This has been achieved in the face of growing pressure due to the worldwide spread of pathogens, larger areas of apparently uniform crop monoculture, and often more favourable in-crop conditions due to greater agronomic inputs. The elucidation some 60 years ago of the "gene for gene recognition" theory by Flor, an Australian, put the understanding of resistance to many biotrophic organisms onto a sounder genetic basis. Major resistance genes have played a critical role for example in the control of wheat rust and some rice pests. But pathogens and pests continue to evolve new virulence against many of the major resistance genes, and although the supply of such genes has been augmented through the exploitation of alien resistance genes derived from wide crossing, and pathogen evolution slowed by gene pyramiding, the battle is far from over as consideration of the current situation with late blight of potato (*Phytophthora infestans*) attests. In a number of cases international networks have been set up amongst crop scientists to monitor pathogen virulence and provide early warning to breeders and farmers of resistance breakdown, for these threats do not recognize national borders. Besides an alternative host plant resistance approach, proposed by van der Plank in the 1960s, based on the notion of "horizontal resistance" and the accumulation of minor rate-reducing genes, appears to be delivering resistance which is more durable. These days in developing as well as developed countries, modern crop monocultures may appear uniform across vaste areas, but it is the diversity of the underlying resistance genes which is critical, and maintaining this defence is probably the most vital role that ongoing crop breeding serves, and the biggest disaster waiting to happen if it is neglected. Lately molecular biology is revealing both dazzling complexity and surprising commonalities across the world of plant-disease interactions, but it appears that practical reinforcement of host plant resistance through this route is not imminent.

Agronomy

Farm level yield progress (as a %/yr) always exceeds breeding progress because **management** is also improving, and because new management often positively interacts with genetic improvement. Progress in US maize yields reflects all these things, including the seeding density by hybrid interactions described above (Figure 1).

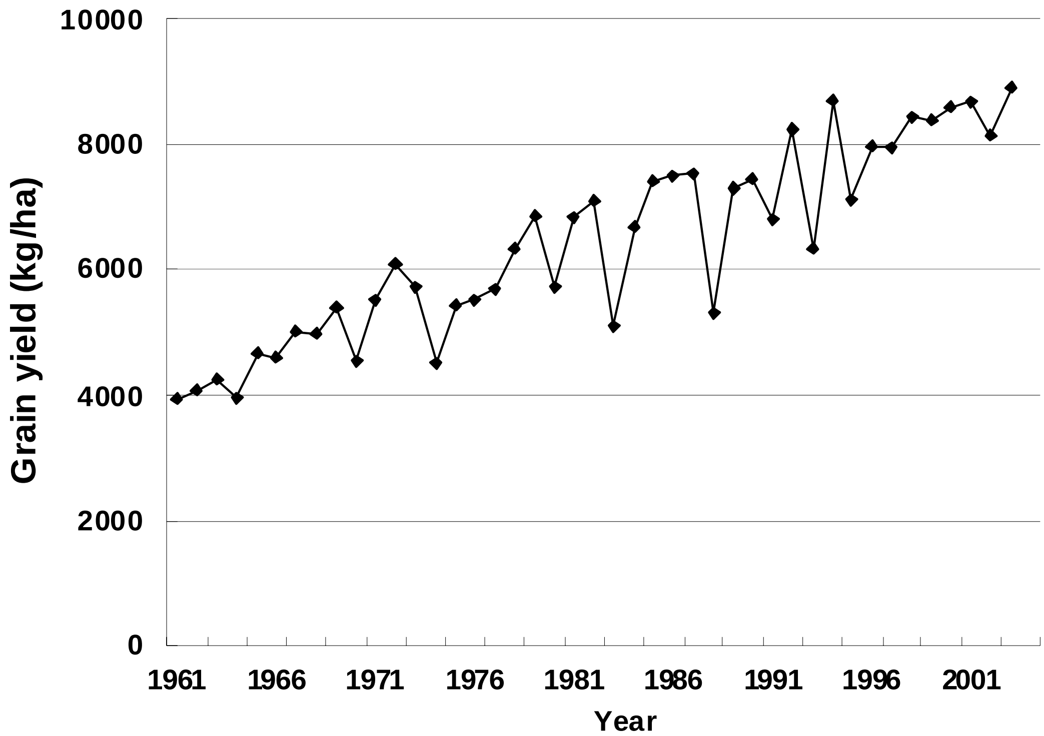

Figure 1 Progress in maize yield of USA

Progress in irrigated wheat yields in the Indian Punjab is an equally outstanding example from the developing world (Figure 2).

The increased use of f**ertilizer** over the last 40 years has been a major management factor in the crop yield growth described in Tables 1 to 3 and Figures 1 and 2. Gross consumption increased 25 fold in developing countries to reach 91 m t in 2002, and but only increased 2 fold in developed countries (50 m t). Use and rates in the former countries surpassed that in the latter in the early 1990s. Interestingly, average rates (kg/ha) in developing countries continue to rise, while amounts and rates in developed countries have been falling since the late 1980s, but this partly reflects the use of higher analysis forms. The main fertilizer element is N and Cassman et al (2003) have recently analysed its use globally, at about 90 m t in total. Current national average cereal yields are closely and linearly related to average N use (range 0 to 250 kgN /ha) with a slope around 40 kg grain/kg fertilizer N applied. Better management and new varieties have improved efficiency, and there are organic N sources, but for the world as a whole it will not be easy to escape this general relationship between grain productivity and fertilizer N, as shall be discussed later in the Congress.

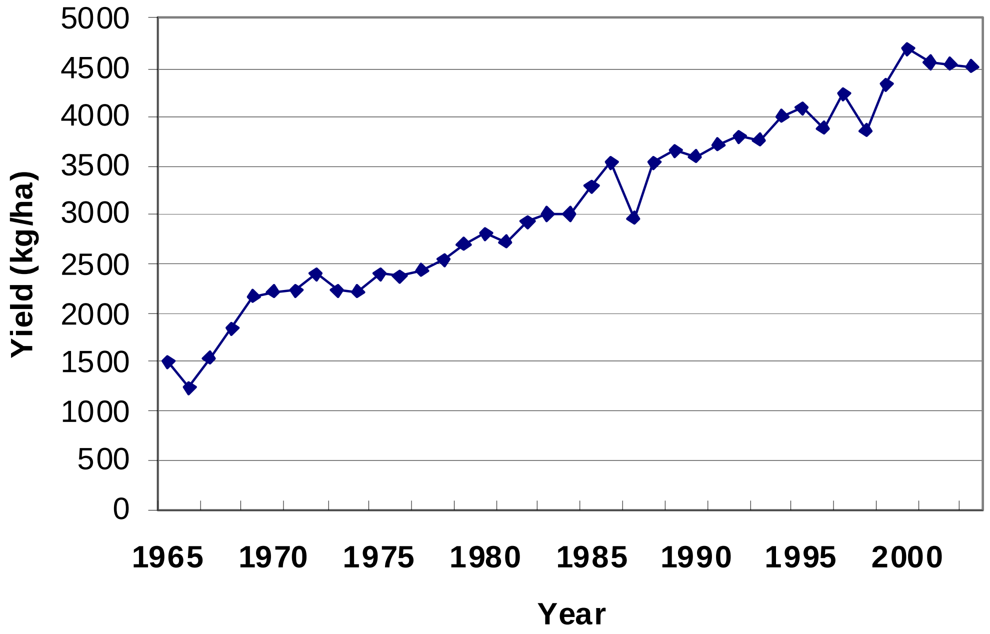

Figure 2 Wheat yield progress, Punjab, India

Almost as important as increased fertilizer use, at least in Asia, has been the expansion of **irrigation**, permitting higher yields (eg wheat in north west South Asia, north China) and higher cropping intensities (thereby increasing crop area, eg summer rice in north west South Asia, boro or winter rice in north east South Asia). It is estimated that irrigated lands have expanded to reach 268m ha with 80% in developing countries and much in Asia; expansion over much of the last 40 years at 2 % pa is now slowing down and average cropping intensity is steady at about 110% (FAO 1998). Improved **weed control**, largely through herbicide use, but also assisted by more timely and effective tillage, is becoming perhaps an equally important factor as any farmer will tell you. Finally we are seeing a revolution in **reduced tillage**, catalysed by new herbicides and spearheaded by early progress in USA, then spectacular progress with direct seeding in Brazil and Argentina, and now reaching Asia and Africa, and promising better yields, cost savings and reduced negative environmental impacts. The crop science behind all these changes is important and has been described many times, and will receive much attention later in the Congress.

In a sense "breeding and feeding" of crops has worked hand in hand to exploit the synergies and give the yield gains described, but it is more than "feeding", which embraces only fertilizer and water, and it is the working together which has been the key to the progress. Crops are part of cropping systems, and these in turn a part of farming systems, and management can impact on much more than "feeding". It is appropriate to illustrate this point by describing the progress in wheat yields in our host nation, Australia, a figure first developed by Donald (1965) and later extended by others (Figure 3). Note that wheat is grown in Australia under dryland conditions with on average only about 300 mm water available per crop, yet there has been great progress, even while crop area has steadily expanded onto generally more marginal lands. Many points are made in this figure, including the possibility of yield decline if the soil is run down, as happened early on. But the key point here is about cropping and cropping system synergies: the importance of breeding throughout, its positive interaction with fertility enhancement, with weed control and with improved soil health through crop rotation, and finally (and very late by world standards) the use of nitrogen fertilizer, which as late as 1980 was less than 5 kgN/ha and even now averages only 30 kgN/ha on wheat (Angus 2001). One reason for this is the continuing reliance on grazed leguminous pastures in rotation with cereal cropping, ley farming to use the original English term, and pointing to a farming system synergy almost unique to Australia amongst developed countries.

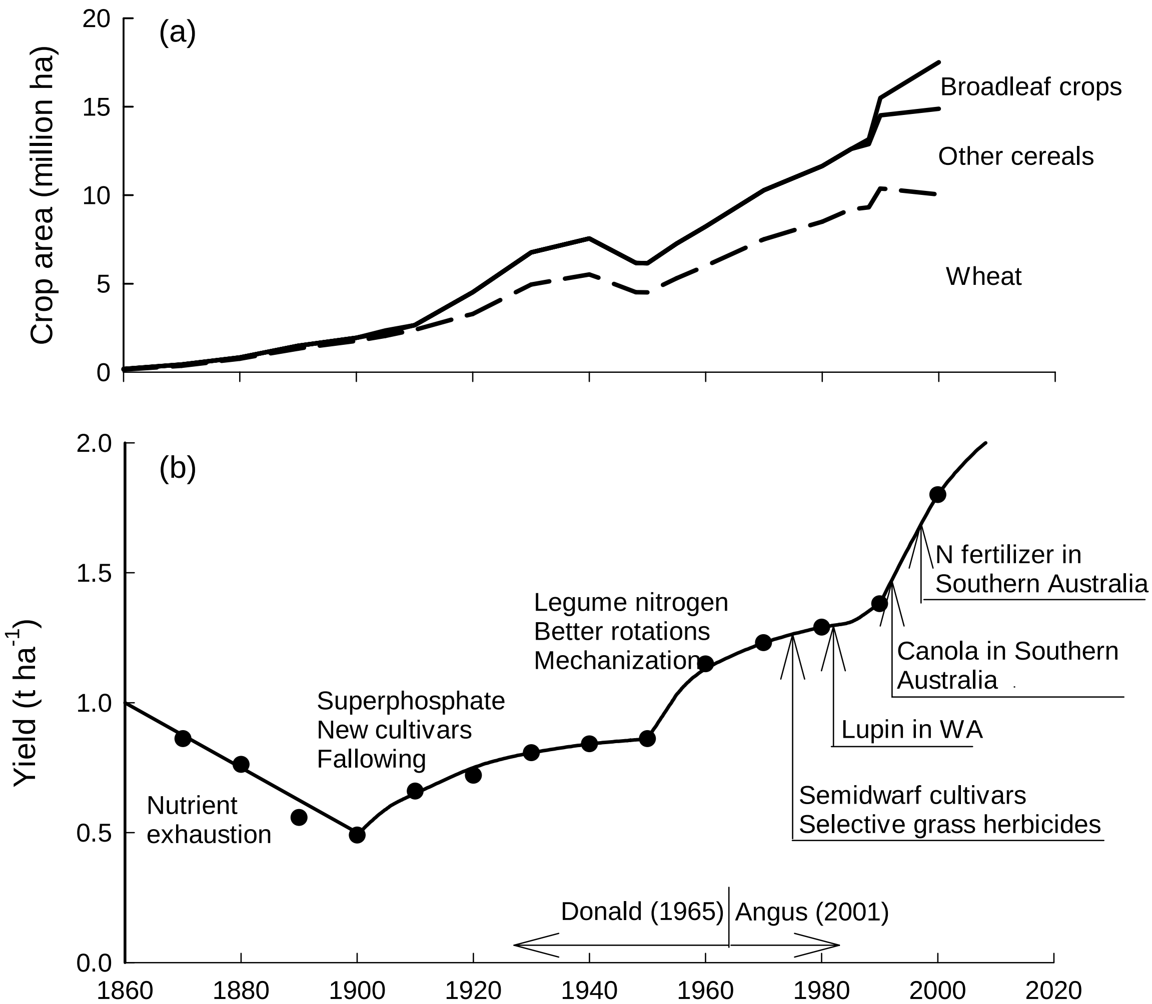

Figure 3. (a) Growth in Australian crop area 1860 to 2000, and (b) decline and rise in wheat yields along with the key factors involved; decennial averages (Donald 1965; Angus 2001)

Fostering farmer adoption

While celebrating the achievements of crop science we should not overlook the role played by what we have traditionally called agricultural extension, and indeed 25% of the Congress is devoted to the issue of "effecting farmer change". Publically-funded extension services, in particular those in North America, with their county agents and close alignment to the research and teaching in the Land Grant University system, linked the farmers to the new crop science throughout most of the last Century. This provided the model for many developing countries, but especially the newly independent South Asian nations in the middle of the century. Suffice to say here that this formal system, where well supported, and in cooperation with input suppliers, sometimes public more often private, has been effective whenever the other conditions were ripe for farmer adoption (absence of institutional and infrastructural constraints). But the developed world is moving on, with the gradual privatization of agricultural extension, and the developing world is confronted with many situations, often the less favourable agroecological ones and those of the poorest farmers, where adoption is seriously lagging and much non-commercial subsistence farming persists. A lot of extension research has been conducted and various new extension paradigms have been tried in these situations over the last 25 years: new principles are emerging, and sometimes old onesrediscovered. These inevitably emphasize greater attention to the farmers circumstances, understanding and perceptions, to farmers' knowledge and learning, to the need for farmer involvement in aspects of the research, to the role of farmer alliances at the village and catchment level, and more recently, to the exciting prospects arising from modern information systems. Many of these important developments will be discussed later in the Congress.

4. Slowing yield growth in last decade

While we can and should rejoice in the past achievements of farmers, scientists, extension workers and policy makers, there is no room for complacency. We will face a host of new problems. Firstly population growth continues apace (best estimates suggest around 8.5 to 9.5 billion in 2050, up almost 50% from now, Duncan and Wilson 2004) and other factors are increasing per capita demand for most crop products (income growth and urbanization, growth in demand for crop-fed animal and fishery products, stagnant wild capture fisheries, growth in non food or feed products). Crop yield simply must continue to grow in order to meet this demand, as well as to counter arable land losses from degradation and urbanization. Only thus can we effectively resist the pressure for the opening up new arable lands, especially as suitable new land is almost non existent in Asia and of limited extent in South America and Africa, and there would be serious environmental consequences with new arable land development wherever it arises. However the yield growth rates of most crops are declining. Table 4 compares the rate for the 30 year period of the 1960s to 1980s with that for the most recent decade (decade up to 2001-2003), and compares the latter with the best bet rate (in the final column) projected by IFPRI IMPACT model for their baseline scenario out to 2020 (Rosegrant et al 2001; Rosegrant MW personal comm.). In many cases actual rates are already close to or below the assumed baseline rates which themselves are rates that leave many undernourished; failure to meet the IFPRI rates means even more malnutrition, poverty and delayed development. The bottom lines of the table show three crop/region combinations which are maintaining high yield growth rates (>2.0%); these are not however major crops, but they may contain lessons for the majors.

Table 4. Yield growth rates (% pa, compound) from 1961-63 to 1991-93 and from 1991-93 to 2001-03, and projected rates for IFPRI IMPACT[1] model baseline (1997-2020).

Crop	Category	Yield growth rate, % pa		
		1961-63 to 1991-93	1991-93 to 2001-03	1997 to 2020.
All cereals	World	2.3	1.0	1.04
Wheat	Developing	3.4	1.2	1.15
	Developed	2.3	0.5	0.68
Rice	Developing	2.6	0.8	1.15
Maize	Developing	2.7	1.7	1.62
	Developed	2.2	1.9	0.84
Roots/tubers[2]	Developing	1.3	0.3	1.27
Soybean	Developing	3.0	2.7	1.62
Rapeseed	Developing	3.1	2.2	Na
Oil palm	Developing	2.0	5.8	Na

[1]Source: M.Rosegrant, 2002 run, personal comm.
[2]Without potatoes

Reasons for the falling aggregate yield growth rates are multiple, and it is useful to consider the two main components of farm yields. Firstly there is the potential yield for the particular crop with the best available variety and soil management, considering the climatic resources available (radiation, temperature, water) and the absence of pests and diseases, something akin to the best experiment station yields. The second component is the gap between this potential yield and the actual farm yield, resulting from the interplay of economics, the actual management including cultivars used, and the manageable inadequacies in the farm soil resource. Considering economics and management limitations in the farmers' real world, one may expect there to be a gap, but one that is not more than 20% of potential yield. In reality it is often much more, and hence also known as the exploitable yield gap. Farm yield growth is therefore the resultant of growth in yield potential and closure of the exploitable yield gap. One may add that change in that part of the natural resource base which is not readily reversed by farm management (eg soil erosion, overuse of the irrigation water supply, exotic pest invasion), and climate change (temperature, rainfall, radiation change and including direct effects of ozone and CO_2 increase) are other factors in farm yield change, but for the discussion here, these can probably be considered fixed. As is obvious, this is an important area of crop science but also a complex one (eg see Evans and Fischer 1998 and Cassman et al 2003), to which time here permits only a brief reference.

Yield potential growth

Yield potential growth is important because it has in the past and should continue in the future to translate in a relative sense to farm yield growth under most farming conditions, provided the new varieties and practices are adopted. Reference has already been made to yield potential growth through breeding (and management interactions) in a number of crops, in which it would appear that growth has been linear upwards at rates ranging from 0.3% to 2.0% pa of current yield levels, depending on crop. However in a recent analysis of the key three cereals, rice, wheat and maize, Cassman et al (2003) has raised doubts as to whether yield potential progress is continuing and points out that in any case the linear rate of increase has become now much less than 1% of current potential yields, and less than 1% compound, the measure used in Tables 1- 4. Doubts are greatest in the case of tropical rice, where studies at IRRI, at least on non-hybrid varieties, show little gain in yield per ha in the last 30 years, although some improvement in yield per day (Peng et al (2000) and later in Congress). Cassman et al (2003) claim there is evidence of slowing in the case of maize in mid western USA, especially noteworthy as probably one of the most intensively researched crops anywhere. Besides there seems little doubt that breeding for yield progress is taking more research resources, and no realistic results yet suggest that genetic engineering will boost yield potential progress soon. Slowing yield potential growth, especially in % terms, does seems to be happening, and as we shall see, is likely a factor in slowing farm yield progress.

Farmers in some cropping systems appear to have completely closed the exploitable yield gap, as judged by average yields in whole districts or regions as good as or above experiment station yields. Many other farmers are not so far below this threshold that their yields do not still reflect in large part the potential of their cultivars and system. For both these groups maintaining yield potential progress is obviously critical for yield growth in their fields. Examples of the former systems would be maize in mid western USA, wheat and rice in north west India (eg Figure 3) and many parts of eastern China, and rice in central Luzon of the Philippines.

Rate of yield gap closure

While farm yield growth responds to (slowing) yield potential growth in the above situations, it also responds to the rate at which any exploitable yield gap is closed through farmers taking up improved crop varieties and management techniques. This gap is still significant for many farmers and regions. Acquiring knowledge about the techniques is one obstacle, infrastructure and institutions represent another. The importance of rural roads and functioning markets for agricultural progress are a reflection of the latter such policy measures which are essential for yield gap closing. In many developing countries, and especially in remote and/or low rainfall and poor soil areas, so-called marginal areas and farmers, the yield gap is still appears to be relatively large. This offers another opportunity for boosting farm yield progress, but the investment requirements are large and lagging commitment on behalf of governments and the private sector to this may be another reason why yield progress is slowing.

It is a mistake to think that yield gap closing is not also the domain of the crop scientist. As mentioned, a significant sector of the Congress is in fact devoted to the theme of crop science effecting change. For example robust cultivars, tolerant of both abiotic and biotic stress (eg a recent example would be Bt cotton), or low cost management interventions, like simple reduced tillage strategies and tools, facilitate progress to close yield gaps (eg recent progress in Brazilian cerrados (acid oxisols) is example of research lifting very low maize, rice and soybeans towards levels closer to the climatic “potential”). And as mentioned earlier, such breakthroughs go beyond technologies to research approaches and scientists’ attitudes.

5. Sustainability

The push for higher yields must be realized without associated ecological harm, a task in which crop science also has huge role. Indeed it will be appropriate to refer to the emerging scientific progress on farms as an "*ever-green revolution*", to emphasise that the productivity advance is sustainable over time since it is rooted in the principles needed to sustain the natural resource base of agriculture, but also it considers the economic, social and gender equity issues surrounding agricultural development.

Ecological sustainability of high productivity will be an important determinant in relation to the choice of technologies. For example, even though modern varieties are more efficient with respect to grain produced per unit of nitrogen supplied and especially taken up, if hybrid wheat can enable us to produce say 10 t/ha, over 300 kg of nitrogen will be needed by the crop. It is obvious that if the nitrogen needs of hybrid or other high-yielding crop varieties are to be met, whether through mineral or organic fertilizers, there will be greater risk of environmental problems, in particular nitrate pollution of ground water and greenhouse N oxide emissions. Hence, success in achieving high productivity on a sustained basis will depend upon our ability to develop new methods of feeding the plant. Research on breeding and feeding should be carried out concurrently by a team of breeders, physiologists, agronomists and soil scientists. Although in some situations there is also risk of off farm phosphorus pollution (mainly related to soil erosion), the extra quantities of other nutrients inevitably demanded by higher yielding crops pose less of an environmental problem than nitrogen (but they must be supplied, often to build fertility, and always in the long run to replace what is removed in product).

Water scarcity for irrigation looms in many parts of the world and a significant part of the Congress deals with this theme. Fortunately, however, yield improvement through breeding and crop agronomy has not greatly increased the water use of irrigated crops (that is per hectare per crop), so that efficiency of water use (yield relative to crop evapotranspiration) has risen along with yield (even deficit irrigation does little to improve this ratio in most crops). This should continue to be the case, crop water use in irrigation being driven by crop duration and climate. But there is great scope for research and development to reduce the non-productive water losses in irrigated systems in the farmers fields, in particular soil evaporation, and drainage below the crop root zone and runoff, where that is not recoverable later in time or elsewhere in space, and likewise reduce losses in water supply to the field. Besides there is need to deal with waterlogging, a common phenomenon of many irrigated systems and arising from poor water application techniques and/or untimely rain, and resulting in decreased yield and lower water use efficiency.

The reduced tillage revolution has the potential to boost for sustainability markedly. In a sense we are returning to Neolithic farming where human effort planted the early crops with little soil disturbance, as can still be seen in the some central American hillside maize systems where seeds are dropped into holes made through the heavy mulch with pointed sticks. Weed control through the use of broad spectrum herbicides heralded the rediscovery of reduced tillage some 40 years ago. Dependence on herbicides for weed control remain the Achilles heel of reduced tillage, but crop science will overcome this weakness. Obtaining and retaining the mulch on the soil surface is the key to the reductions in erosion and water loss, if not also the weed control, but also has its major challenges, especially where in drier areas biomass production is limited and in warmer ones where decomposition rates are high; besides wherever there are ruminants there is competition for the biomass, and in some impoverished systems, it has fuel uses. And finally, human and animal traction will disappear from farming, for as development occurs mechanical traction is inevitably adopted, firstly two wheeled tractors of no more than 10 hp on up until today’s 8 wheel beremoths of 300 hp and more. But it is these wheels and the weight they carry which most compacts the soil and creates a need for even more tillage. Controlling wheel traffic offers huge advantages in this regard: control can be as simple as confining traffic to furrows in permanent bed and furrow systems, or as complex as robotic steering guided by GPS.

It is not only reduced tillage which depends on herbicides, for most commercial agriculture in developing as well as developed countries these days is thus dependent, and often dependent on fungicides and insecticides as well. Host plant resistance plays a major part in lessening the latter dependence, and can only get more reliable considering the new tools available to breeders. Hand weeding will becomes prohibitively expensive with development, so staying ahead of the weeds will loom larger as a challenge, and will call for every weapon the crop scientist can muster. Currently, herbicide-resistant crop varieties, often genetically engineered, represent a powerful new weapon, but it is likely weed evolution will eventually lessen their effectiveness.

6. Genetically modifies organisms (GMOs)

The elucidation of the double-helix structure of the Deoxyribose Nucleic Acid (DNA) molecule in 1953 by Drs. James Watson, Francis Crick, Maurice William and Franklin Rosalind marked the beginning of what is now known as *the new genetics*. Research during the last 51 years in the fields of molecular genetics and recombinant DNA technology has opened up exciting new opportunities in agriculture, medicine, industry and environment protection. The ability to move genes across sexual barriers has led to heightened interest in the conservation and sustainable and equitable use of biodiversity, since biodiversity is the feedstock for plant, animal and microbial breeding enterprises.

Considerable advances have been made during the last 25 years in taking advantage of the new genetics in the areas of medical research, production of vaccines, sero-diagnostics and pharmaceuticals for human and farm animal health care. The production of novel bioremediation agents as for example, the development of a new *Pseudomonas* strain for clearing oil spills in oceans, rivers and lakes by Dr. Anand Chakraborty, is also receiving priority attention because of increasing environmental and water pollution.

There has also been substantial progress in agriculture, particularly in the area of crop improvement through the use of molecular marker assisted breeding, functional genomics, and recombinant DNA technology. A wide range of crop varieties containing novel genetic combinations are now being cultivated in USA, Canada, China, Argentina and several other countries, the total area exceeding 67 m ha in 2003 (James 2003). A strain of cotton containing the *Bacillus thuringiensis* gene (Bt Cotton), which has resistance to boll worms, is now under cultivation. Besides cotton, the largest areas in the world under genetically modified varieties are in corn, soybean and canola. Some major developing countries, such as India, China, Brazil and South Africa, are now actively participating in the science of this revolution.

There is little doubt that the new genetics has opened up uncommon opportunities for enhancing the productivity, profitability, sustainability and stability of major cropping systems. It has also created scope for developing crop varieties tolerant/resistant to biotic and abiotic stresses through an appropriate blend of Mendelian and molecular breeding techniques. It has led to the possibility of undertaking anticipatory breeding to meet potential changes in temperature, precipitation and sea level as a result of global warming. There are new opportunities for fostering pre-breeding and farmer-participatory breeding methods in order to continue the merits of genetic efficiency with genetic diversity. It is doubtful however that there is likely to be impact on yield potential, so critical for yield maintaining progress, in even the medium term future. Yield under abiotic stress has been targeted by many labs and there are many papers in the Congress on this issue, with conflicting views on the chance of early impact on crop yields. However in the area of biotic stress resistance there have already been successes and more should follow.

While the benefits of GMOs are clear, there are also many risks when we enter the territory of the unknown and unexplored. Such risks relate to potential harm to the environment and to human and animal health. There are also equity and ownership issues in relation to biotechnological processes and products. The following issues are the major areas of concern to the public and policy maker.

- **What is inherently wrong with the technology?**
  Is the science itself safe, as for example, the use of selectable marker genes conferring antibiotic or herbicide resistance?
- **Who controls the technology?**
  Will it be largely in the private sector? If the technology is largely in the hands of the private sector, the overriding motive behind the choice of research problems will be private profit and not necessarily public good. If this happens, “orphans will remain orphans” with reference to choice of research priorities. Crops being cultivated in rainfed, marginal and fragile environments, which are crying for scientific attention, may continue to remain neglected.
- **Who will have access to the products of biotechnology?**
  If the products arising from recombinant DNA technology are all covered by intellectual property rights (IPR), then the technology will result in social exclusion and will lead to a further enlargement of the rich-poor divide in villages.

- **What are the major biosafety issues?**
  There are serious concerns about the short and long term impact of GMOs on the environment, biodiversity and human and animal health. Besides they could foster greater genetic homogeniety across world crops.

Thus, there is need for transparent and truthful risk-benefit analysis in relation to GMOs, on a case-by-case basis. In the coming decades, enlargement of the gene pool with which breeders work will be necessary to meet the challenges outlined above. Recombinant DNA technology provides breeders with a powerful tool for enlarging the genetic base of crop varieties and to pyramid genes for a wide range of economically important traits. The safe and responsible use of biotechnology will enlarge our capacity to meet the challenges ahead, including those caused by climate change. At the international level, the Cartagena Protocol on Biosafety provides a framework for risk assessment and aversion. At the national level, there is need for a regulatory mechanism, which inspires public, political and professional confidence. Some developing countries, in particular China, India, and Brazil are beginning to invest substantial public funds in GM crops; this may balance the concern expressed by many over the current high degree of ownership of enabling technologies by the private sector. But sharing with smaller and poorer developing nations will continue to be an issue.

7. Climate Change

Climate change arising from human activity and associated greenhouse gas build up and aerial pollution seems to be accepted by the general scientific community, at least with respect to warming, although there is dispute about its magnitude and about effects on precipitation. Recently Australian research highlighted another change, namely declining evaporation (Roderick and Farquhar 2002), which appears to be linked to reductions in the solar radiation reaching the surface of the earth, due to more cloud and /or more atmospheric aerosol pollution. Predicting effects on future climate is difficult enough but prediction of effects on crop yields even more so. Many predictions are for reduced yields, especially in lower latitudes where developing world agriculture is mostly located. Some studies seem to be able to point to yield reductions already. For example a thorough study by Aggarwal et al (2000) of rice and wheat yield trends in north west India over the period 1980 to 1995 point to yield declines under non-limiting nutrients and water, likely the consequence of temperature trending upwards and solar radiation downwards. More recently Peng et al (2004) linked rising night temperatures to declines in dry season rice yield at Los Banos in the Philippines: they reported a yield decline of 10% per degree rise, and measured rises of 0.5 degrees per decade.

While it is not possible to speculate about possible loss of arable areas and irrigation resources due to climate change, there is no doubt that future crop varieties (and management practices) must be adapted to future climates. This could well require access to all of the genetic diversity available in crop plants. Besides, we should foster integrated programmes of pre-breeding and participatory breeding with climate change in mind. Pre-breeding will help to generate novel genetic combinations, while participatory breeding with farm families will help to combine genetic efficiency with genetic diversity. Numerous location specific varieties can be developed in this manner. This will be the most effective way for meeting challenges arising from potential changes in temperature, precipitation, sea level and biotic stresses as a result of global warming.

8. Equity in agriculture and crop science

Equity has many facets. The substantial progress in aggregate food production per capita in Asia hides the fact that many undernourished poor remain, while in Africa there is yet to be progress in per capita food production. Thus there are 800 million under nourished in the world, with almost one half of these in South Asia and one quarter in Sub-Saharan Africa. This represents a huge inequity. Crop science has a role in alleviating this, and the following opening speakers will give special attention to this issue, but suffice to say here that crop science alone cannot solve the problem: non farm rural (and urban) employment must be created by agricultural and general economic growth combined with targeted policy interventions.

A more specific aspect of equity for crop scientists is the ownership of plant genetic resources. The Convention on Biological Diversity (CBD) stipulates that plant exploration, collection and introduction should be based on the principles of prior informed consent and equity in benefit sharing. FAO has facilitated the development of the International Treaty on Genetic Resources in Food and Agriculture which was recently ratified. This may protect equity as envisaged in the CBD, for the exchange of crop genetic resources in the future will be possible only on the basis of Material and Knowledge Transfer Agreements. However much detail remains to be worked out. The recent discovery by Brazilian researchers of a naturally decaffeinated coffee in germplasm collected in Ethiopia will be a good test of whether a rule based system can be made to work to everyone's satisfaction.

A further and related aspect of equity in crop science is that of access to new technologies for crop research and cropping, technologies usually arising in the developed world. We are witnessing an expansion of proprietary science governed by Intellectual Property Rights (IPR). The green revolution was the outcome of public good research. Unfortunately, public good research supported from public funds, is now shrinking. What will be the impact of such a situation on international varietal or other trials organised by IARCs? Is the golden age of cooperative research coming to an end? How can we find a balance between public good and private profit? Will the fruits of the gene revolution triggered by molecular breeding be available to resource poor farmers? And yet there is the possibility that just as India made big inroads in global IT, with their low cost well-educated scientists, so also could they, along with China and others, take over in biotech (with or without multinational involvement), in this case helped by a less negative emotional attitude of the public towards biotech. This would also ensure that biotechnology research focussed on crops and problems of greatest interest to the developing world. But much needs to be done in the area of relevant IP regulations, and also biosafety regulations.

9. Conclusion

There has been great agricultural progress in which crop science has played a justly proud part. But the next 3-4 decades will be critical for the world and demand equally substantial progress in yields, accompanied by increased resource use efficiency. Investment in successful science like conventional breeding and agronomy and agricultural extension cannot be lessened, but nor can new technological possibilities be ignored or pursued in isolation from the conventional. Besides the farmer cannot be overlooked in this process, nor the broader public who will largely pay for (but ultimately benefit from) this crop science. Hopefully this Congress will foster the sharing of ideas and learning that will help in these processes.

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