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Only clever science will yield crop results

Chinese proverbs can often be deeply philosophical or downright idiotic. I have a favourite which sums up why I work in agriculture and why I get irritated by debates about skin blemishes on apples, EU pesticide reduction policies and organic farming feeding the world.

"A person who has food has many problems. A person who has no food has only one".

Chinese proverb

A more recent quote is less eloquent but equally stark:

"We have more hungry people in the world today, than we ever had in the history of human kind." Kostas Stamoulis, the Secretary General of the Committee on World Food Security.

This is not just because the global population is rising and hungry people represent a proportion of the population - the hunger rate has also begun to rise - meaning the number of hungry people is growing at a faster rate than world population.
A Cabinet Office document, nicknamed by Tim Lang, Professor of Food Policy at City University, the "Leave it to Tesco Report", argued that we are a rich developed nation which could buy its way out of any supply crisis on the global market. The UK produces about half of the food consumed here, and is about 60% 'self-sufficient'. Most UK food imports come from elsewhere in the EU (68% in 2006) and the UK considers itself well placed to access the food it needs from world markets, where required (The "Leave it to Tesco" approach). Global grain stocks are high so why worry? However, many of these stocks are strategically stockpiled and not available on the world market - so when Russia decides to ban exports of grain (August 2010) this sends prices skyward. Of course we in the west can survive such price hikes but in developing and emerging economies the challenge is in some cases a matter of life and death. In these countries food represents a much higher proportion of household budgets than in the West, and they are less able to withstand such shocks.

Words such as 'local', 'seasonal' and 'organic' have become very fashionable and have, in the UK, been referred to as the 'holy trinity' of food production. But these are merely lifestyle choices for the affluent middle-classes of Europe and will never begin to tackle global food insecurity.

Increasing yields will also be needed if agriculture is to meet world demand for both food and energy. Any number of estimates of global population growth exist but as reliable as any is that of The World Bank - which estimates that cereal production needs to increase by 50% by 2030 to meet food demands. This is a massive challenge. The same estimate has been used by Prof John Beddington, the governments Chief Scientific Adviser who qualified this estimate by adding limitations on the use of inputs - "We need 50% more production ….on **less land**, with **less water**, using **less energy**, **less fertiliser** and **fewer pesticides**...by 2030" – an even greater challenge.

So how can science help?
We can increase crop yields in 2 ways:

Increase the <u>attainable yield</u> of crops by reducing losses due to pests, diseases and abiotic stresses.

Increase the <u>potential yield</u> of the crop.

Reducing losses due to pests, diseases and weeds is what we have been very successful at over the last 30 years. The crop protection industry has consistently delivered more and more effective products, tackling the problem of resistance development, discovering new areas of chemistry – all within increasingly stringent legislation to improve safety and protect the environment. We have also learned how to optimise those inputs and developed decision support systems to help growers and advisers to implement what is often termed 'integrated pest management', but what is really just modern farming methods including the use of resistant varieties, adjusting sowing rates, nitrogen doses, using thresholds etc. I believe that the agrochemical industry is now beginning to struggle to deliver ever more active (and yet environmentally benign) products and we cannot expect them to continue to deliver as they have in the past.

In the UK we have had dramatic yield increases in crops in the last few decades. Over the last 60 years we have doubled average yields of wheat twice – from just over 2 t/ha in the 1940s to 4 t/ha in the 1960s and now at just over 8 t/ha. These increases came about from investment in production-orientated research which delivered high yielding varieties which responded to increased inputs of fertilizer and pesticides. The best UK wheat growers now routinely achieve yields of 10-12 t/ha. The limitation on these growers is now water availability and the amount of solar radiation that is available to the crop. The varieties currently grown are clearly capable of much higher yields – they have a higher potential yield that is not attainable in the UK. Take these varieties to New Zealand, give them sufficient nitrogen and water and they will deliver yields almost double our national average. The current theoretical yield potential of wheat is estimated to be close to 20 t/ha. This target of achieving wheat yields of 20t/ha is one of the strategic goals of Rothamsted Research.

The largest contribution to the increased yield potential of modern wheat varieties came from the increase in harvest index. There was a quantum leap in harvest index from the introduction of dwarfing genes into varieties developed the 1960s. These varieties also allowed higher rates of nitrogen to be used. Breeders will claim much of the glory for the dramatic yield increases but increased nitrogen use and crop protection products undoubtedly played significant roles. Currently, fungicide use in official HGCA CEL trials delivers on average a 20% yield response. This dependency on fungicide inputs is a feature of wheat production systems, wheat breeding and climate in the UK. The yield of wheat and its response to fungicide use in other EU countries is considerably less.

Further increases in yield potential depend on an increase in canopy photosynthesis per unit of intercepted light or a decrease in the metabolic costs of synthesis and maintenance of carbohydrates, proteins, and lipids. To date there is little evidence that plant physiologists or breeders have been successful at increasing the assimilatory or metabolic efficiencies of the major cereal crops. Therefore, the most likely scenario for yield potential of the major cereal crops is one of small, incremental increases during the next three decades, and these modest improvements will require considerable research investment. Even with investment in applied science this incremental increase in yields will not allow us to reach the challenging targets imposed upon us by increasing global population.

The global demand for wheat is predicted to increase at a faster rate than the annual genetic gains that are currently being achieved. Consequently it is generally agreed that improvement in genetic yield potential will need to be accelerated in order to avoid the otherwise inevitable destruction of sensitive ecosystems. Those production targets demand radical change to our crops and cropping systems.

Targets for change:

Increasing attainable yield: The 12 t/ha wheat crop
Wheat crops of 12 t/ha are not uncommon in the UK. Good growers on good land would expect average yields in the order of 10-12 t/ha. Clearly the genetic potential for such yields already exists but the average UK yield of just over 8.0 t/ha seems tenaciously difficult to move. Many farmers and advisers are now well-qualified technically (many BASIS-qualified) but there must be scope for increasing the technical knowledge of farmers and advisers. Beyond raising the technical level of training of those involved in farming there is still scope to achieve increases in the attainable yield by further research into optimising inputs (water, nutrients, pesticides), and delaying senescence (by reducing disease effects and maintaining canopy growth).

Clearly the genetic potential for 12 t/ha yields exists in our current varieties as the current world record wheat yield of 15.6 t/ha was achieved in New

Zealand using the variety Einstein (A Nickersons variety, almost 10 years old!). The world record crop was grown on deep silt soils in New Zealand with high radiation levels and no water deficit – conditions we cannot reproduce in the UK.

Increasing potential yield: 20 t/ha wheat crop

To begin to tackle the targets imposed by global population growth we must be more radical than just tinkering with inputs. To meet a production target of 50% yield increase by 2030 we need to alter the fundamental biology of the crop.

Radiation use efficiency

The yield potential of a crop (YP) can be expressed as a function of the light intercepted (LI) and radiation-use efficiency (RUE), the product of which is biomass and the subsequent partitioning of the biomass to yield, i.e. harvest index (HI):

YP=LI x RUE x HI

There are already some good indications that we can increase yields significantly by increasing the radiation use efficiency of the crop. There is increasing belief that wheat may be 'sink-limited', i.e. the crop may be able to produce more biomass but there is insufficient storage capacity for the carbohydrate. More grain sites per ear (bigger ears) would help increase that storage capacity. Thus, improving the balance between source and sink is a highly promising approach for raising RUE, biomass and yield.

Carbon Fixation / Drought tolerance

C_4 plants such as maize have a competitive advantage over plants possessing the more common C_3 carbon fixation pathway under conditions of drought, high temperatures, and nitrogen or CO_2 limitation. Increasing photosynthetic capacity, either by modifying wheat to C_4 metabolism or selecting for C_4 traits, must be a major target for breeders. Under the same growth conditions, C_4 grasses lose less than one third of the amount of water per CO_2 molecule that is fixed, compared with C_3 grasses. This increased water use efficiency of C_4 grasses allows them to grow for longer in arid environments. Forty-six percent of grasses are C_4 including maize and sugar cane. Introducing this trait into wheat could increase yields dramatically. Even in the UK, 30% of wheat is grown on drought-prone land, equating to potential losses of up to £60 million/year. This situation is only likely to become worse with climate change. A simpler but more radical approach may be to select for existing C_4 plants such as maize which are adapted to UK climatic conditions.

Broadening the genetic base of wheat is also often quoted as a necessary route to achieve these targets. To achieve these targets will require a multidisciplinary approach and close co-operation between fundamental and strategic research on the one hand, and applied plant breeding on the other.

Timescale for crop changes
The timescale for yield improvement is critical. Many of the traits or characteristics that are desirable for increased crop yield are difficult to achieve and without biotechnology (genetic modification of crop species) are unlikely to be achievable in the short to medium term. The suggested timescale for potential crop changes is outlined below. Many of the short to medium term solutions are increasing the achievable yield. Increasing the potential yield is a much more challenging target and is on a much longer timescale.

Short-term solutions (less than 5 years): (Increasing achievable yield)
New approaches to crop management.
New pesticides that directly affect crop physiology.
Better fungicide programmes, disease reduction.
Improved input management.
Seed treatments to protect against pests and diseases.
Medium-term solutions (10-15 years): (Increasing achievable yield)
Breeding and genetic modification of new varieties of crops that are resistant to disease, drought, salinity, heat.
Longer-term...speculative (> 15 years): (Increasing both potential and achievable yield).
Development of nitrogen fixing cereals.
Perennial crops which won't need frequent replanting.
Development of C_4 crops which would boost the efficiency of photosynthesis.
Breeding existing C_4 crops to adapt to different climates.
Improving hybrid crops and apomixis (maintaining hybrid vigour without the need for parental crossing).

Tools for research and technology
The research tools are either for genetic or phenotypic analysis of plants. The genetic analysis targets their DNA whereas the phenotypic investigations involve their biochemical, physiological or morphological characteristics. Complete genome sequences of crop plants and microbes are particularly important because they provide detail about all of an organism's genes and the proteins that the organism can synthesise. Genes or combinations of genes affecting crop production can be easily identified using genomics. In genetic improvement strategies these genes can be targeted in breeding programmes or they can be transferred into crops by GM.

Non GM Approaches
There are 3 distinct phases in conventional breeding - creation of variation, selection and then evaluation. Conventional crossing of crop varieties or breeding lines can get you so far but creating greater variation from which to choose can be challenging. This is long been achieved by the use of

chemical mutagens or radiation. Radiation has long been used to produce mutations in a significant proportion of the world's crops, including rice, wheat, barley, pears, peas, cotton, sunflowers, peanuts, bananas, cassava and sorghum. These crops are now widely grown and 'conventional'. The FAO has promoted the application of nuclear technologies in agriculture since 1950. So far, more than 3,000 new varieties have entered mass production worldwide for commercial purposes.

There is a view that the major world crops have reached a genetic 'glass ceiling', meaning that no matter how much more conventional crossing is done there is simply not enough genetic diversity available to significantly improve their agricultural value. This view is not held universally but it seems clear that conventional breeding techniques are not currently delivering the yield increases demanded by population growth.

GM Approaches:

In genetic modification (GM), novel genes are introduced, either individually or in small groups, into a crop plant. The genes inserted may either be:
from the same species (cisgenics) or
from another species (transgenics).

Genetic modification can produce a plant with the desired trait or traits faster than classical breeding because the majority of the plant's genome is not altered. GM-based methods are used widely as a routine tool in research and they have greatly facilitated major advances in plant biology over the last 25 years. In the USA, Argentina, Brazil, India and Canada, GM crops are grown widely (134 million ha in 2010), whereas in Europe and Africa (except South Africa) they are largely absent. The majority of these GM crops are insect resistant (Bt crops) or herbicide tolerant (HT crops). Such GM technology can have dramatic effects on the attainable yield of crops and can have environmental benefits in terms of reduced pesticide and nutrient use. This relatively simple technology is often referred to as 'first generation' GM. Second generation GM crops under development aim to improve yield by improving salt-, cold- or drought-tolerance. The same technology may also begin to increase water-, nutrient- and radiation-use efficiencies. Only second generation GM crops will have a significant impact on the potential yield of crops.

Targets for GM approaches:

Modification of photosynthetic efficiency (C_4 v C_3 crops).

C_4 photosynthesis is more efficient than C_3 and is found in drought-tolerant grasses such as maize and sorghum, but not in wheat and rice. This is, like many research targets, a 'Holy Grail' target as it would increase the potential crop yield.

Perennial crops.
These are often talked about and may well offer environmental benefits because of reduced tillage and hence reductions in greenhouse gas emissions but they are unlikely to increase yields *per se*.

Nitrogen fixation in non-legumes.
Again a 'Holy Grail' target for researchers. This would reduce the huge energy demand of producing nitrogen fertilisers but again is unlikely to increase yields. In fact there is very likely to be a yield penalty for the introduction of such a process into a plant species.

Abiotic stress tolerance.
Abiotic stresses are those derived from non-living factors such as drought, salinity, heat. Increasing water uptake from soils (while ensuring that water is available at critical developmental periods) can be a useful strategy, which is why phenotyping of root characteristics is receiving so much research attention. This would almost certainly increase yields dramatically. Worldwide, drought stress is probably the number one restriction to growth of crops.

Biotic stresses.
These are the pests, diseases and weeds that steal so much crop yield worldwide. For that reason there has been intensive research into genetic and crop management strategies to mitigate these losses. In many respects this research into plant defence has been highly effective and there are many examples of current and emerging crop protection strategies. However, complete success is impossible because weeds, pests and pathogens continue to evolve to overcome plant defence systems and agrochemical interventions.

Plant breeding for disease resistance.
It is not immediately obvious but most plant species are completely resistant to most diseases. Pathogens are generally specialised to infect only certain plant species and cannot infect the vast majority of other plant species. This is termed 'non-host resistance' (NHR). For example, rice is resistant to cereal rusts, and tobacco is resistant to potato late blight. Understanding the molecular basis for NHR could enable more durable resistance to be engineered into crops.

RNAi and Gene silencing.
RNA interference (RNAi) is a vital part of a plants normal immune response to viruses and other foreign genetic material. This can be induced in plant material – making the plants immune to certain diseases – much like vaccination in animals. In this process <u>no new genes are introduced, not even from same species</u> . However, this can currently only be done with GM technologies.

Introducing novel genes (Transgenics).
The wider deployment of GM approaches will be needed for the introduction of novel genes from diverse sources. The constraints on regulatory and consumer acceptance of GM are still considerable in many parts of the world (particularly Europe). Consumer acceptance may be greater and regulatory approvals simpler in future where plants are transformed with cisgenic vectors in which only host gene sequences are used.

Hybrid vigour (Heterosis) and Apomixis.
For inbreeding species such as rice and wheat, hybrid vigour can theoretically offer very large (<50%) yield increases. However, there are many challenges and constraints to this technology and as such it is not yet fully developed in a wide range of crops. The next step in developing hybrid vigour would be apomixis, where plants produce seed without the need for fertilization. This allows hybrid vigour to be 'fixed' so that crops do not need to be bred from different parental lines.

Crop protection chemicals.
Pesticides (Perhaps we need a better name?) are used widely to protect against weeds, pests and diseases. These compounds are the mainstay of global crop protection and they are likely to remain so for the foreseeable future. New chemistry resembles chemicals present in plants that activate natural resistance mechanisms and, because they do not target pests and pathogens directly, they could have environmental advantages and be perceived by the general public as 'safer'.
Chemical modification of plant metabolic processes is now commonplace. 'Fungicides' no longer just control fungal diseases – they can also control viral and bacterial diseases via host defence triggers. They can increase nitrate uptake, increase root activity and water use efficiency, delay senescence. These are not fungicidal products *per se* but fall into that category of EU pesticide legislation.

A New Language and a New Approach
We need to develop and promote terms that the general public are comfortable with (but may not understand, any more than they understand 'GM'), such as 'vaccination' or 'immunisation' rather than 'genetic modification' or 'gene silencing'. 'Biotech crops' may be more acceptable than 'genetically modified' 'Natural defence promoters' may indeed currently be called 'pesticides' and yet they may have no direct toxic effect.
Scientists need to be much more careful about promoting their science and they need media training so that they can manage the way their science is promoted. All too often scientists are lulled by the media into promoting the bizarre – taking about jelly-fish genes and genes from spiders being incorporated into plants and animals – whilst completely failing to explain any benefits. They use inappropriate language, concentrate too much on the

science without thinking about benefits and end up falling into the trap of scaring the general public.

Conclusions:
Research is essential to ensure that yields are at least doubled in the next 50 years. The research dilemma is that we have to feed a rapidly increasing world population – there are only 2 choices: increase yields or plough up land with high biodiversity – accepting an almost certain acceleration of climate change with the latter.
Achieving these scientific advances is possible, but present levels of investment in these specific research areas are currently not adequate to meet the challenge. Public investment in scientific research is key but we are rapidly losing skills in the industry through an historic lack of investment. This includes key research skills but also the skills of knowledge transfer which many researchers lack. The ability to translate research findings into key messages for industry is a skill that is important if research is to have social and economic impact.
Much of the technology to produce much higher yields is currently scientifically possible but is not being applied as much of it relies on genetic modification procedures. The confusion around the use of the term 'GM' is undoubtedly a hindrance to progress. For example, should a food from soya be labelled 'GM' if it has been genetically engineered to have a gene from another soya plant or only when it has a gene from another plant species? Equally, what if the 'GM' product (e.g. vegetable oil) is identical to the non-GM version (i.e. there is no 'foreign' DNA present? This is the argument for concentrating on the product and not the process by which it is produced.

All technology should be adopted provided that it is safe and sustainable. The concept of 'sustainable intensification' of agricultural production should be accepted and promoted – i.e. growing the highest yields possible on the least amount of land, whilst protecting valuable biodiversity elsewhere.

Finally, a thought from a modern philosopher:

"We live in a society exquisitely dependent on science and technology, in which hardly anyone knows anything about science and technology".
Carl Sagan

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