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HOW TO MATCH SUPPLY TO DEMAND

Harnessing plant science for food security

KEY THEMES

- Interaction between food supply, demand, yield and sustainability.
- Revolutionary tools and methods of modern plant science.
- Radical innovations that could transform future agriculture.

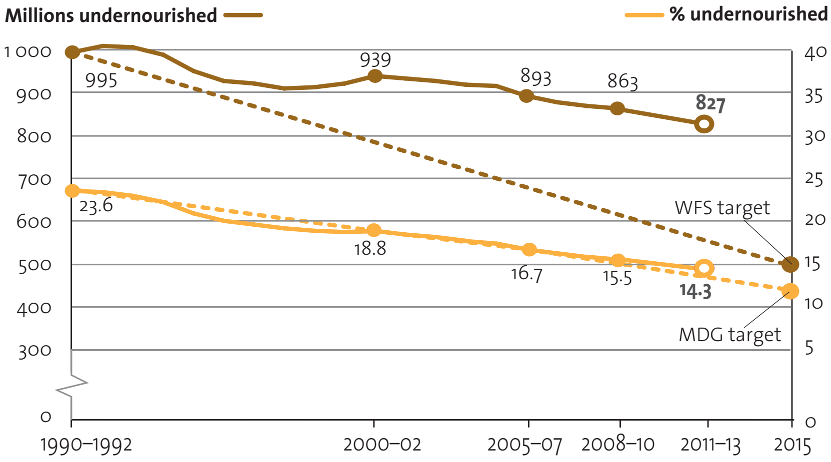
Two lines of attack

Global food security needs a two-pronged attack: reducing demand for food along with increasing sustainable crop production. Both will be necessary if recent developments in plant science are to be harnessed optimally. Technological innovations will be most effective if rolled out as integrated components of agricultural systems, as the case studies in this chapter illustrate.

As far as demand is concerned, food security would clearly benefit from a slowing of population growth, improved food distribution mechanisms, reduced consumption of meat from grain-fed animals, and minimising the immense waste that currently takes place both before and after harvest. With comprehensive measures to address these issues, the challenge of increasing crop production would obviously be lessened.

Unfortunately, however, there is little cause for optimism that the demand side of the equation can be tackled. The United Nations Millennium Development Goal of halving the *proportion* of undernourished people between 1990 and 2015, for example, is not so far from being realised, but the World Food Summit target of halving the *number* of hungry is a long way behind schedule (Figure 1.1), largely

Figure 1.1 State of the world's food insecurity, 1990–2013



Source: FAO

The number of food-insecure people in the world, 827 million in 2013, has fallen in recent decades, but not fast enough to meet the 2015 World Food Summit target.

due to population growth. We have, instead, to look to the other side of the coin – that of increasing supply through improvements in production.

In doing so, it is vital to take into account problems of sustainability and increasing yield. Current production is not always based on sustainable practices. Indeed, crops at present occupy around 12 per cent of the land surface of the Earth, which has colossal implications for the environment – depleting natural resources, degrading ecosystems, polluting groundwater through pesticide and fertiliser use, and damaging the atmosphere by driving up levels of nitrous oxide, a potent greenhouse gas. Future climate change will undoubtedly make matters worse by changing rainfall patterns and increasing desertification, and by subjecting crops to the stress of extremes of temperature and flooding.

This means that strategies for meeting future needs have to embrace increases in yields while deploying more sustainable production methods than those currently in use. A further complication is that there are few regions where more land will be available for cultivation without adversely affecting the environment: only existing agricultural land can be used effectively.

Researchers have made quite spectacular progress in understanding plant biology down to the level of individual molecules.

Crop yields in regions with industrialised crop production systems can exceed 10 tonnes per hectare, but output is constantly limited by environmental and sustainability considerations. There is regional variability as well. Whereas parts of Central and South America and much of Asia benefited from the first Green Revolution, yields in Sub-Saharan Africa have largely stagnated. Had the continent increased agricultural yields by just 1 or 2 tonnes per hectare, there would have been dramatic improvement to both local and global output.

The role of plant science

There are various ways of improving output, not all of them involving new technology. Subsidising the cost of fertilisers and pesticides is one example. The focus here, though, is on the contribution of technological innovation.

The term “revolution” is often and justifiably applied to modern plant science in which genetics plays a major role. Researchers have, over the past couple of decades, made quite spectacular progress in understanding plant biology down to the level of the individual molecules that constitute the genetic machinery. This has led to powerful new tools for improving crops, both by manipulating their genomes and by enhancing conventional breeding methods.

Among these tools is the ability to generate sequence data for DNA or RNA to the point of cataloguing the entire genome of organisms: all their genetic information and their whole transcriptome – all the different types of RNA molecules in their cells. What is more, this can now be done quite quickly and cheaply. Today, the challenge is not so much to generate data as to make sense of it through computational analysis – and science can now use powerful bioinformatics programs to slice, analyse and interpret these large datasets.

Cellular imaging, too, has taken big strides forward. Today's advanced microscopy systems produce far better images than simple microscopes. Plant tissue can be penetrated deeper, and far more data can be made available for computational analysis than was possible only a few years ago. This means that subtle changes in sub-cellular structures far below the limits of detection of normal light microscopes can be directly monitored: the effects of genes and the proteins they code for can now be seen in action.

Chemical analysis of the composition and characteristics of plant extracts has also become more sophisticated using the tools of mass spectrometry. Today it is possible to monitor previously uncharacterised proteins or other components of plant cells at critical transition points, such as during development or in response to external stimuli. Again, microscopic biological processes can be tracked as they actually happen.

How do these extraordinary advances in plant science translate into improved crop production? The three case studies on the following pages illustrate how the new science links not only with modern biotechnology, including genetic modification (GM), but also with more classical approaches such as organic and other low-input methods.

Golden Rice, rice genetically engineered to biosynthesise beta-carotene, could save lives in places where there is a shortage of dietary vitamin A – estimated to cause the death of around 670,000 children under five every year.


www.goldenrice.org

The coming of age of genetic modification

Gene cloning, genetic mapping and advanced DNA sequencing have all become everyday automated reality in the genetic revolution of the past few decades. All have profound repercussions for the future of agriculture.

- Genetic modification has several advantages over conventional cross-breeding techniques. For one thing, crossing one plant with another and then selecting the most appropriate progeny often necessitates repeated procedures: backcrossing a plant with its parent a number of times in order to achieve a variety that possesses the desired trait. For another, it obviates

CASE STUDY Push-pull systems in East Africa

Insecticides to control pests and the diseases they carry can undoubtedly be effective in eliminating unwanted insects. But they often have the disadvantage of being indiscriminate, targeting insects other than the pest. Insect-resistant varieties of some crops do exist, but not necessarily the ones a farmer needs or can afford.

An alternative strategy is based on the use of plants which produce chemicals that can powerfully affect the behaviour of insect pests. These signalling chemicals – semiochemicals – influence mating or feeding behaviour, as attractants or repellents. One successful application of this approach is the control of stem-borer moths that attack maize in East Africa, based on a push-pull strategy sometimes referred to as companion cropping.

It works like this: a maize field is surrounded by a border of forage grass – *Pennisetum purpureum* – which provides the "pull" by being more attractive than maize to stem-borer moths seeking a site for laying their eggs. It also generates a gum-like substance that kills the pest when the moth larvae enter the grass stem. This constitutes a first line of defence.

In addition, rows of maize are intercropped, or interplanted, with rows of the forage legume silverleaf (*Desmodium uncinatum*), which releases semiochemicals that repel the stem-borer moth from the maize: the "push" mechanism.

An added bonus is that silverleaf also fixes atmospheric nitrogen in root nodules, thus enhancing crop nutrition. Not only that, it is also toxic to another weed plant – the parasitic African witchweed or *Striga* – which is capable of wiping out whole maize crops if left unchecked.

Practicalities: pros and cons

There are considerable advantages to a push-pull strategy. Because it controls but does not eliminate a pest, there is little selection pressure on the offending insect to develop insecticide resistance. This makes it a more environmentally sustainable and possibly durable method than pesticide use.

However, this is still a relatively unadopted technology and is not seen to be broadly applicable or effective in Africa. Nor has it enjoyed wide application in intensive or larger-scale industrial agriculture – for three reasons:

1. Companion cropping, even when apparently working well, gives lower yields than crops cultivated intensively using fertilisers. It is therefore economically unattractive, though this will probably change over time with rising fuel costs and an incentive to use less energy.
2. The costs of the agricultural engineering and machinery necessary for companion cropping arrangements are also high, although this too could change as farmers learn more about optimising their resources.
3. There is some way to go in understanding the basic science of how plants and pests interact.

The better our understanding, the more precisely, cost-effectively and sustainably will farmers be able to adopt push-pull methods.

CASE STUDY Priming for defence

Crop protection chemicals, for all their obvious advantages, have a few limitations. They can be useful against insects and fungi, but are ineffective on bacteria or viruses. They are also prohibitively costly for, say, subsistence farmers. They can have unintended adverse effects on the environment or farmers and people living nearby. And many pests and pathogens acquire resistance to them.

One alternative chemical strategy being explored by plant scientists is to target not the pest itself but the inbuilt defence machinery of the threatened plant.

Plants can draw on a defensive mechanism known as systemic acquired resistance (SAR). If infected by one pathogen they become resistant to a second invader, in the following manner. Once a pathogen attacks a plant it triggers a long-distance signal that stimulates defensive responses away from the invasion site. Specifically, the signal switches on a set of genes that code for proteins with anti-microbial properties which combat the pathogen.

Likewise, there is another kind of defensive mechanism – induced systemic resistance (ISR) – that can be activated when beneficial microorganisms colonise plant roots. Again, a signal is sent through the plant's vascular system to trigger immunity in the parts of the plant growing above ground.

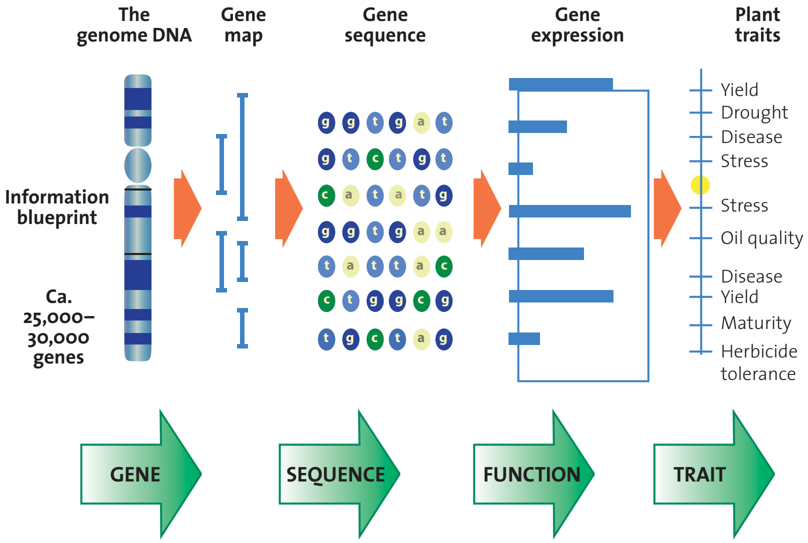
Both SAR and ISR have been shown by researchers to be effective against a broad range of virulent plant pathogens. How then can this knowledge be used? The theory is that synthetic chemicals that mimic plants' signalling molecules could be applied to exploit these inbuilt defence systems by inducing a "memory" mechanism that would persist, with no need for further chemical applications. These mimics would have broad-spectrum effectiveness because the defensive mechanism they induce is not specific to any particular pathogen: a genuinely multi-purpose protection.

That, at least, is the theory. To date, these priming compounds have not been widely used in the field as they need to be applied ahead of infection and new technologies for monitoring and detection would have to be developed. Furthermore, the experimental compounds that have been tested vary in their performance.

Despite these limitations, the priming technique is a promising and durable alternative to pesticide-based methods. The consensus is that it justifies more investment in research to identify suitable compounds.

linkage drag, whereby the crossing procedures result in the introduction of other, linked genes that adversely affect the selected crop. With GM, the gene that determines the desired trait is transferred more quickly and precisely with no unwanted linked genes finding their way into the recipient plant.

Figure 1.2 Genome sequencing for a desired characteristic



- Using GM to transfer genes between plants has the advantage that a gene can be inserted into several varieties suited to different localities with different agricultural conditions.
- Genetic techniques directly manipulating an organism's genome using biotechnology will become more flexible and useful than they have been to date. The first generation of GM crops mostly used genes transferred from bacteria – an enzyme called 5-enolpyruvoylshikimate-3-phosphate (EPSP) synthase, which conveys herbicide tolerance, and Cry (standing for crystalline) proteins for insect resistance. Herbicide tolerance and insect resistance were derived from bacterial genes and virus resistance from viral genes. That is changing. Now that genes associated with desirable traits can be isolated as stretches of DNA, genetic manipulation can be used to transfer genes from a crop or crop relative into the target plant using standard transfer techniques. One example of such a transgene is the fungal-disease-resistant potato developed by transferring a fungal-blight-resistance gene from a wild potato relative into a commercial agricultural potato.
- The ability to sequence the genome that contains genes of interest, although likely to be hundreds of genes, not just one or two – those conferring improved yield for example – also finds applications in conventional plant breeding. Breeding programmes designed to develop desired crop traits and characteristics may be speeded up and costs reduced. In addition, our

Conventional plant breeding has been very successful but historically it has been an imprecise art. The new molecular technologies, including genome sequencing – which identifies the precise order of the four bases adenine, guanine, cytosine and thymine in a strand of DNA – are changing this. The scientific basis of all crop improvement is the identification of the genes that encode and regulate specific traits of benefit to the farmer.

continuously developing knowledge will make it possible to breed crops with traits for yield and drought resistance that are regulated by a multiplicity of genes, not just one.

Future grand challenges

The case studies in this chapter illustrate how current science and the novel technologies it drives could contribute to sustainable crop production, with yields that are adequate to meet a growing demand. However, while radical in themselves, these advances are really no more than valuable refinements to existing crop production technology and farming practices. Looking to the future, far more fundamental innovations could change agriculture beyond recognition. For this to happen, three challenges need to be met:

- Cereals and other crops that today are annuals will need to become perennials. (It has been suggested that humans may in fact have originally chosen annual varieties because they could be selectively bred quickly by saving the seeds of desired plants each year.) With perennial varieties, the

CASE STUDY New kid on the block – homologous gene targeting

Recent research has resulted in a novel approach to crop improvement: homologous gene targeting. In essence, this is a way of targeting changes to plant genomes to create useful mutations with properties such as toxin production for protection against pests or enhanced crop growth and development.

The science underpinning targeted modification of genomes turns on the discovery of a set of enzymes called transcription factors, which copy genetic information encoded in DNA to messenger molecules – RNA – as the first step in synthesising more proteins within the plant cell. These transcription factors – TAL effectors – control whether genes are switched on or off at specific sites along the DNA molecule.

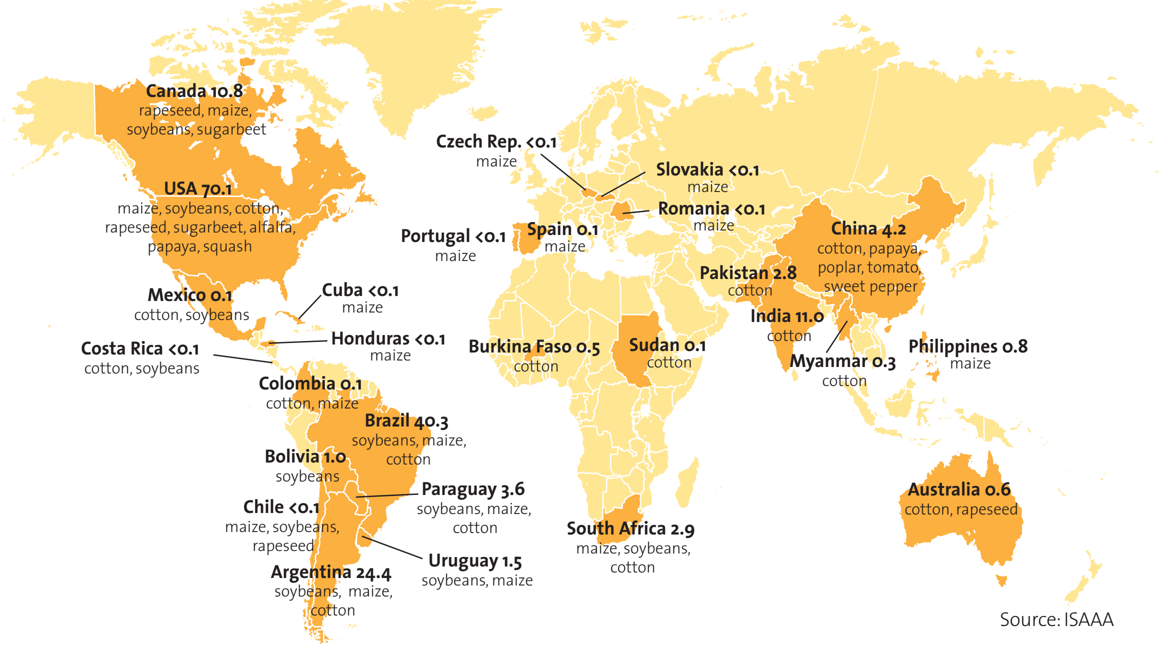
TAL effectors can be used as a route of entry for DNA from outside sources modified to incorporate specific mutations with beneficial effects, such as the ability of a plant to become resistant to a specific pathogen. They allow these desired mutations to enter the recipient genome at a precisely determined point such that they become totally incorporated within the host plant's genetic machinery.

Once plants have been exposed to this newly acquired DNA, the targeted modifications can be propagated as part of the genetic material of a new and improved variety.

These technologies have only recently been developed and are yet to be shown to be a feasible way forward in practice.

Figure 1.3 Commercial genetically modified crops worldwide, 2013

Million hectares



Source: ISAAA

aerial part of the crop would be cut, or allowed to die back, but its root systems would remain undisturbed to grow again and produce above-ground leaves and seed in subsequent years. Conventional breeding would struggle to achieve perennialisation, but gene transfer techniques that carry the trait of perennialisation from wild crop relatives could well deliver this benefit. The impact of perennial grains and other crops in both developing and developed countries would be game-changing because replanting every year would no longer be necessary. Breeding of new varieties would still be needed, however, both to combat evolving pests and pathogens that become resistant and to adapt to changing climatic conditions.

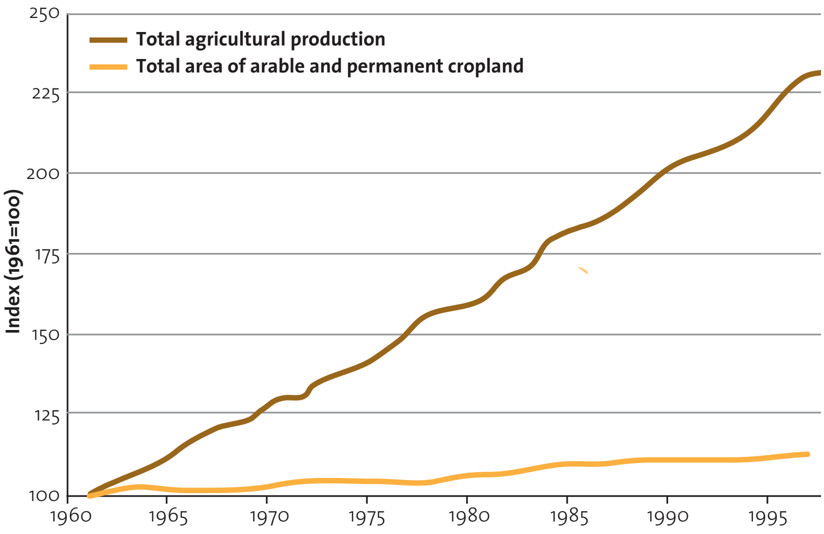
In 2013, some 18 million farmers across 27 countries grew genetically modified crops over more than 170 million hectares.

- Photosynthesis needs to improve in efficiency. In photosynthesis, the basis for all life on this planet, plants make organic compounds from carbon dioxide (CO2) and water using the energy from sunlight. They do so in a complex sequence of biochemical events involving a number of metabolic pathways. In some major crops such as wheat and rice photosynthesis can be wasteful, with non-productive and energy-consuming processes impairing CO2 uptake and fixation efficiency. But in other plants this limitation has been overcome by an alternative pathway coming into play

At the global level, productivity increased steadily during the second half of the 20th century while the area of cropland under cultivation rose by only 10 per cent. This was thanks to four major areas of innovation:

- **mechanisation and irrigation;**
- **synthetic fertilisers;**
- **pesticides and fungicides;**
- **plant breeding and genetics.**

Figure 1.4 Twentieth century innovation: can it happen again?



Source: FAO

to act as a metabolic shunt, or shortcut. If an artificial version of this could be designed through genetic engineering, crops might benefit from a photosynthetic pathway that could greatly enhance their productivity. Again, basic research could lead to such a radical improvement.

- The final grand challenge is to improve food crops other than wheat, rice and maize which, today, account for more than half of global calorie consumption. Major crop yields have increased sevenfold since the beginning of the 20th century as a result of spectacular improvements in farming methods: mechanisation and irrigation together with the use of crop protection chemicals and synthetic fertilisers coupled with plant breeding and genetics – the Green Revolution. Could something similar be achieved for those hitherto neglected, orphan or underused crops such as sorghum, cowpea or millet, which are the staple food of many millions of people in developing countries but have enjoyed little attention until recently? Here, surely, is an open goal for basic science in the century ahead.