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Biodiversity, biotechnology and agriculture

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THE ULTIMATE IMPERATIVE—FOOD FOR THE WORLD

One of the biggest challenges facing mankind in the coming century is how to feed the world's burgeoning population. Despite the enormous successes of agriculture, over the next 30 years food production must increase dramatically as the population jumps from 5.8 billion this year to just under 9 billion by 2030. The effect of this simple numerical increase will be compounded by the changing diets of large sections of the populations of countries with improving economic circumstances. Increases in meat consumption indicates an even greater growth in the demand for cereals for animal feeds than cereals for direct food use. In Asia, grain production will need to double and Latin America faces a major challenge. In Africa, yields are currently well below the genetic potential of the crops that are grown, so efficiencies are imperative but much food will still need to be produced elsewhere. These interactions mean that the demand for food will increase by close to 100% in the first quarter of the 21st century.

Where and how is this food going to be generated? The impressive food production increases of the past 30 years have been achieved through the synergistic interaction of better management, increased inputs and increased genetic potential. Is it realistic to expect continuing success at this or an even greater rate, especially in the light of increasing additional constraints arising from mankind's belated recognition of the parlous state of the world's environment? More than ever before, producers are being forced to take a longer-term view of the environment, increasing yields whilst taking care of the biotic and abiotic natural resources of their lands, ensuring sustainability of the production enterprise.

From the producer or farmer's point of view, the objective of his agriculture is to maximise profits whilst providing for a continuing production enterprise. Unfortunately though, given the vagaries of weather conditions that effect crop production, and unpredictable fluctuations in both buyers' preferences and the volume of competing production elsewhere in the world, care for the natural resources of cropping areas often takes a back seat to the immediate economic imperatives of short-term survival. We need to recognise that sustainability of production systems will not be achieved without reliable profitability being built into the system. Profit comes from both yield levels and, increasingly in different crops, quality differentiation fitting the product to market requirements, this usually attracting a premium price. In both these areas, genetic improvements and management practices contribute markedly to the farmer's livelihood. Genetics really is concerned with yield potential whereas management is important in the longer term for sustainability, and in the shorter term for achieving optimum yields with minimum and timely inputs. Improvements brought about by both genetics and management practices are important for the farmer but management practices alone, at this time, are addressing the sustainability issue, the agricultural system component.

PROTECTING THE BIOTIC AND ABIOTIC RESOURCE BASE OF AGRICULTURE

Production agriculture operates in modified environments—even in subsistence agriculture natural environments are changed. This need not be detrimental to adjacent natural environments nor need it be debilitating to the production areas, however agriculture has unfortunately led to negative effects on the biotic and abiotic components of the environment.

With regard to the care of biotic resources, extensive genetic resource collections for the major cereals exist, and as far as can be judged, a large proportion of the primary and secondary gene pools of these crops is now in safe keeping and available for plant breeding programs. Although much work has still to be done to improve the intellectual and physical infrastructure needed for efficient accessing of the genes stored in these gene banks, plant breeders have, and continue to successfully use these resources to develop higher

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yielding varieties, especially of rice, wheat and maize. Other grain crops such as sorghum and millets are covered by large collections but basic biological knowledge of their representativeness is incomplete. In general, with the exception of potato, the world's major starchy crops have received far less attention than the cereal crops. One of the difficulties for the starchy crops is that conservation is generally in field gene banks; as a consequence existing collections are primarily stocked by cultivated varieties. However, recent advances in *in vitro* conservation methods are making it possible to envisage a more extensive set of collections in the future. Knowledge and care of the species interacting with the production species is another matter, particularly of soil microorganisms—knowledge in this field and consequent good practice are in their infancy.

Past agricultural practices have often given no thought to the maintenance of all-important abiotic resources. As a consequence, erosion, increasing acidification and salinisation have become extreme in many parts of the world, taking what was previously some of the best land out of production. Increasing awareness of the despoiling of both the soil and water resource is leading to the development and use of better management practices with a considerable research focus building on water availability and the appropriate use of fertilisers. Genetics will certainly play a role in both countering and reversing these negative trends, yet the genetic improvement of crop species for greater efficiency in water use and in the acquisition of nutrients, is only just becoming a reality.

BIOTECHNOLOGY AND BIODIVERSITY

The food production increases of the past 30-40 years have been achieved without large increases in the total agricultural production area. However, this apparently reassuring figure is misleading, being achieved only by an increasing utilization of previously unused marginal lands as many prime production areas are swallowed by continuing urban expansion. Since these marginal areas are often important refuges for biodiversity in the agricultural landscape there is cause for concern. In developing countries, another 12% of lands could be brought into agricultural production (Kendall *et al.*, 1996), while even in highly developed agricultural systems in Australia, Europe and the United States, small patches of bush, hedgerows and woodlots are potentially "usable"—but with what effect on biodiversity conservation?

Modern intensive agriculture with its demands of high yields and uniform performance is often cited as a cause of loss of biodiversity. Now that biotechnology, particularly in the form of genetic engineering is being used to enhance the performance of our production plants, it too has been nominated as a threat to biodiversity. Is this really true? What are the links and relationships between biodiversity, biotechnology and agriculture, and how can we orchestrate these for maximum benefits and minimum damage on all fronts? Obviously, where agriculture encroaches on sensitive ecosystems, destroying habitats, then it may reduce biodiversity. However, another diversity concern,—that biotechnology leads to the replacement of landraces and region-specific strains or lines of a cropping species, with high performing cultivars,—does not need to result in loss of genetic variation. Biotechnology does reduce the genetic diversity being used in the cropping system at a given point in time, but for a variety of agronomic reasons the use of single cultivars over huge production areas is a practice now coming under challenge and biotechnology is key to a new trend. In the short term, biotechnology may hasten the trend for cultivars to become more internally uniform in genetic makeup, but already an opposing trend in our highly developed production systems is to provide highly targeted, regionally-specific and market-specific cultivars—cultivars which deliver the requirements of high yield and quality under the particular soil and climatic conditions of each production area—modern day landraces!

Another factor in the monoculture consideration is the role of public and private breeding teams and increasingly in their mode of interaction. Public breeders generally place sustainability at a higher priority than private breeding companies who are under pressure to maximise profits. Intellectual property issues may well be the principal vector in this particular equation. Strategic alliances between public research institutions and the large multinational companies in life sciences are shaping agribusiness. The terms of these alliances are important for each nation, determining their roles in global agribusiness.

The continued growth of agricultural production depends on genetic diversity to overcome biotic and abiotic challenges and to provide for increased performances. New germplasm must also provide for the changing quality traits demanded in our food and fibre commodities and products. Gene technologies have increased the dimensions of the gene pool available for cultivar improvement and at the same time have increased our capacities to detect appropriate genetic variation. These new breeding tools are increasing the rate of development of new and higher-performing cultivars.

Apart from their impact on highly mechanised, large-scale agriculture, the new technologies can, and hopefully will be, of advantage to the small subsistence farmer of rural areas in developing countries. If the various international and national research and agricultural agencies interact appropriately then the benefits of biotechnology could contribute to an increased and more reliable yield of better quality food products even at the family land holding level. The fact that gene technology advances are delivered through a farmer friendly package, the seed, should enable this desirable circumstance.

BIODIVERSITY AND GENETIC DIVERSITY

Breeders are continually working at improving the germplasm available to farmers introducing new cultivars which have improved yield prospects and the ability to counter the challenges provided by pests and pathogens. To do this breeders rely on genetic diversity and mostly that which exists in their breeding pyramid, the primary gene pool. A well planned breeding program incorporates a broad base of genetic variation and in most instances the breeder will be able to find genetic variants to meet challenges that occur. Sometimes, and especially in the more sophisticated breeding programs of cereals, breeders will acquiring important genetic variation from closely related species which can cross sexually with the crop species (the secondary gene pool). In the secondary gene pool those species which have wide ecogeographic distributions are particularly valuable. In wheat it is remarkable that the wonderful potential of *Triticum tauschii* has only been realised in recent years. This species, which contributed the D genome to hexaploid bread wheat, can be readily crossed into our modern cultivars. Accessions from its wide distribution range are proving rich sources of genes for disease and pest resistance, and tolerance to environmental stresses.

As breeders have realised that useful genetic variation lies outside those species which can be sexually crossed to the developed crop, various techniques have been developed which in some cases have enabled the tertiary gene pool or more distantly related plant species to be tapped for a needed gene. This previously rare circumstance is now changing dramatically with the development of gene technologies which extend the gene pool for the breeder, not only to the more distantly related species but virtually to the genetic makeup of any living organism. This is a great development for plant breeders and will contribute significantly to the needed increases in production, but it also highlights the need for conservation of life forms with the subsequent preservation of genetic variation.

GENETIC DIVERSITY AND BIOTECHNOLOGY

Cotton production in Australia is an excellent example of an agricultural industry which has shown remarkable growth in the last two decades, growth which has been dependent on both improved management practices and improved cultivars. The genetic improvement of cotton cultivars in Australia gives some classic examples of the way in which breeders have used genetic variation from the primary, secondary, tertiary and, just in the last two years, quaternary gene pools.

Australian cotton, sources of genetic variation: Over the last two decades, the cotton industry in Australia has grown from one producing $34 million worth of lint from a single valley irrigation system to an industry producing over $2 billion worth of lint from a region ranging from subtropical central Queensland to temperate central New South Wales. Breeding advances have made significant contribution to this development by providing continuing yield increases as well as protection against the major pathogens, *Xanthomonas* and *Verticillium*.

One of the major breeding successes involving character transfer from the primary gene pool has been the incorporation of a dissected leaf character (Okra leaf) into many cultivars. This single gene character provides host-plant resistance benefits against Lepidopteran pests, **and** particularly against mites. Changes in the edge to surface area ratio that accompany the Okra leaf character bring changes in the leaf micro-environment that reduce the need for insecticide sprays. The efficacy of this character is greatest in more temperate cotton growing areas and thus provides an example of the rationale behind the developing trend towards region-specific cultivars in modern high production agriculture.

From the secondary gene pool of closely related *Gossypium* species, *G. barbadense* has been the source of genes that provide tolerance to the *Verticillium* wilt pathogen. This pathogen is a major threat to cotton production, and in the absence of resistance, yield losses of 25% or more (one bale per acre) have been incurred.

The tertiary gene pool of *Gossypium* is particularly rich in Australia where there are a number of species in the native flora. Although exploitation of such distant relatives is notoriously difficult, Australia's wild relatives offer such a rich source of variation that a concerted effort is being made to gain access to the wide range of potential benefits, including genes for tolerance to saline and acid soils, drought tolerance and differences in biochemical properties of the seed oils (Brubaker *et al.*, 1997). One attractive character is the gossypol-free seeded trait of *G. sturtianum*. In cultivate cotton, *G. hirsutum*, the chemical gossypol is produced in glands throughout the plant including the seed where it functions as a feeding deterrent to insects. This compound has to be removed from cotton seed meal before it can be marketed for animal consumption. But in the Australian native, *G. sturtianum,* gossypol is produced in leaves and stems but not seeds, a desirable state of affairs if it applied in our cultivated cotton. Crosses between *G. sturtianum* and *G. hirsutum* are sterile but fertility can be restored by the doubling of chromosomes and backcrossing to generate self-fertile derivatives. These then allow selection to generate lines which are basically stable *G. hirsutum* in genetic makeup but hopefully with the new gossypol-free seeded character. Problems remain because of the apparent paucity of recombination events between *sturtianum* and *hirsutum* chromosomes.

The advent of gene technologies has provided a quaternary source of genetic variation of particular value. This has already been introduced into our cotton ahead of the attempts to bring in genetic material from the wild *Gossypium* species. The bacterial gene coding for the insecticidal protein (*Bacillus thuringiensis*, *Bt* endotoxin) has been re-engineered so that it is an operative gene when incorporated into the cotton genome. The transgenic cotton (INGARD, product of a collaboration between Monsanto and CSIRO for most varieties that are being used in Australia) has provided the first example of the use of a transgenic crop cultivar in Australia. In its first season the transgenic INGARD cotton provided protection from the major Lepidopteran pest *Heliothis*, reducing the need for insecticide sprays by some 60%.

In the second year of release, 15% of the crop area has been planted to transgenic cotton, an area that is limited, not by farmer demand, but by the regulatory body overseeing the use of transgenics in Australia. The principal reason behind this limitation is to ensure the implementation of strategies aimed at preventing the build up of insect resistance to this novel protective mechanism. Indeed, it was just such a build up of resistance in *Heliothis* to chemical pesticides that posed the major threat to the industry which is being relieved by the introduction of the transgenic. To prevent a repetition of a successful evolutionary response by *Heliothis* and other lepidopteran pests, two gene systems are being incorporated into the cotton plant. Each of these systems will have an independent mode of deterrent for insect damage and together should provide a stable and long lasting resistance against the pest species. A number of approaches are under way. One is the incorporation of a second *Bacillus thuringiensis* gene that has a completely different receptor system to the current gene system that is deployed, but there are other possibilities. For example, attempts are being made to have the cotton plant produce in its leaf cells, insect viruses which when transferred to any biting Lepidopteran larva will quickly multiply and kill the larva thus prevent further damage to the plant.

This example of genes from a distant source of genetic variation emphasises what might be achieved in a range of our production plants. It is highly probable that gene tailoring and the provision of specific genetic variation for production efficiencies or for particular quality traits will become a regular component of plant improvement systems from now on.

Transgenics—the next generation

The extended gene pool will provide breeders with novel genetic variation, probably for every function, trait and developmental stage of crop plants, but one of the most exciting areas at the moment is in relation to the host-pathogen interaction. The tools of gene technology that have brought about a radical change in our understanding and the isolation of natural resistance genes are providing an unprecedented opportunity to protect our production plants from a range of pathogens. Gene technology is also opening up the possibilities of building synthetic resistance genes. One spectacular example of resistance against a pest species is provided by the transfer of an α-amylase inhibitor gene from the French bean to the field pea.

The activity of this gene in the pod and seed protects against the depredations of the pea weevil, a major pest of the crop in south eastern Australia. The deployment of this gene in our agriculture could make the difference between a viable situation and total crop failure.

Disease and pest resistance can have spectacularly impressive effects and it is perhaps not surprising that these characters are ones targeted in the first generation of transgenic plants. However, not all transgenics will be based on resistance genes. Australia is the major producer of the lupin grain legume crop, an important source of animal feed but one which is deficient in sulphur amino acids. The addition of a gene from sunflower coding for a sulphur-rich albumin has significantly boosted grain sulphur amino acid in the lupin, and animal tests show live weight gains indicating improved nutritive value of the transgenic crop.

BIOTECHNOLOGY AND CONTAMINATION OF BIODIVERSITY

Potential problems of escape of transgenes into weed and native plant populations: Concerns here focus on three areas—(i) the potential for the transgenic crop species itself to become a weed that might threaten other cropping systems or fragile or disturbed native habitats; (ii) the potential for particular transgenes themselves (for example, pest, disease or herbicide resistance) to spread to related plant species; and (iii) potential changes in agronomic practices that may have significant secondary effects.

In all these areas there has been a considerable diversity of opinion and concern. One conservative strategy has been to identify virtually all relatives of particular crop plants (both weedy and native) as being at risk of change through the incorporation of transgenes. Thus a recent extensive list by Sindel (1997) that combines the potential of transgenic varieties to hybridize with existing cultivars, with their potential to hybridize with closely related weedy species or native plants, tends to inflate the size of the problem. For example, a 'high' risk potential for the spread of transgenes from *Linum usitatissmum* into weedy relatives is listed for four related species recorded in Australia (*L. bienne, L. catharticum, L. marginale* and *L. trigynum*) even though only interspecific crosses with one of those species will only (*L. bienne*) will generate fertile seed. The strategy of comprehensive listing of all relatives of transgenics may be defended as one which errs on the side of caution, but it equally runs a great danger of 'crying wolf' too often.

However, this is not to suggest that the potential for transgenes to spread to weedy species is not real. Indeed, in the Australian farming scene, the interaction between cultivated and wild oats provides a good example of the potential dangers that must be address if the application of transgene technology is to avoid creating agricultural problems as well as leading to significant gains. Thus in Australia, cultivated oats (*Avena sativa*) and three weedy species (*A. barbata, A. fatua* & *A. ludoviciana*) form an interesting and difficult-to-control crop-weed interface. All of these species are common hosts to a number of damaging diseases, and the wild species have been implicated as sources of both inoculum and pathogenic variation in the rusts *Puccinia coronata* and *P. graminis avenae* that may attack and substantial reduce the yield of cultivated oats (Burdon *et al.* 1983; Oates *et al.* 1983). Wild oat seed is also an important contaminant of cereal grain that leads to significant financial penalties. Under these circumstances, *A. sativa* would seem to be a prime candidate as a target for breeding programs aimed at introducing disease and herbicide resistance. However, *A. sativa* and *A. fatua* readily intercross and natural hybrids occur at a frequency of ~1% (Burdon *et al.* 1992). As a consequence, any transgenes introduced into the agricultural crop will, under the influence of disease and herbicide selection, rapidly flow into at least one of these weedy relatives.

This example also illustrates a further ramification that may arise should transgenes that clearly can affect evolutionary fitness, move beyond the crop boundaries. In a mirror-image reflection of the use of pests and diseases to control invasive weeds through biological control programs, the novel disease or pest resistance manipulated through transgene technologies may increase invasiveness and competitiveness of transgene bearing plants relative to non-transgenics as well as other unrelated species in the surrounding vegetation (Hoffman 1990; Raybould & Gray 1993). In many parts of the world *Avena* species are invasive, spreading not only as weedy of other agricultural systems but also into disturbed native grassland and savanna woodland habitats. In these situations their rapid growth may reduce the growth of native species, while their high biomass production and annual habit may lead to substantial increases in fuel loads which in turn may alter fire regimes (Frankel *et al.* 1996). The consequences of such possibilities both in making individual environments more vulnerable to further invasion by other exotic species, or in changing the balance of native species may be considerable.

An additional way in which transgene technology may have a significant effect on farming ecosystems is more indirect but nevertheless still very real. The incorporation of herbicide resistance into a wide range of crops through transgene technology is seen as a powerful means of eliminating weed competition through the direct use of specific herbicides during the growth of resistant crops. However, herbicides have been a significant agronomic tool for many years and this experience has already shown the propensity of many weedy species to respond to long-term selective pressures exerted by herbicides like simazine and sulfonyl ureas through the evolution of tolerant races.

While the development of a new range of herbicide tolerant crops through transgene technology offers increased flexibility in crop husbandry and better weed control, this will only give long-term gains if due attention is given to the likely evolutionary response of the target weeds. Thus the development of cotton varieties which individually carry tolerance to the herbicides basta, bromoxynil, glyphosate and 2,4-D provides a broad array of weed control options. Used in rotation such varieties would provide a very powerful means of preventing the development of weedy races tolerant to any one of the herbicides. However, pyramiding such tolerances into a single cultivar may select for novel forms of resistance which would have widespread agronomic effects that would flow throughout the entire farming ecosystem.

Gene technology is having its greatest effect in increasing our knowledge of biological function and biological developmental processes. One of the current exciting areas in plant science is uncovering the first clues as to the genetic control of the process of seed development. Many natural species of plants are able to develop seeds without the necessity of a sexual pollination (double fertilisation) process. Ultimately when the key genes of this apomixis process are identified, it may be possible to have them operate under an inducible promoter system. In this way transgenic plants that have an outcrossing breeding system may be controlled to produce seeds in the field only by the apomictic process. This would negate the potential of spread of transgenes as a consequence of an outcrossing breeding system.

BIOTECHNOLOGY AND AGRICULTURE

There is no doubt that gene technologies are going to be of great value to agricultural production in a world faced with an ever increasing demand for food. In some instances characteristics of the biological and agricultural systems in which they are to be applied will warrant careful thought and control over the introduction of the new technologies. There could be significant ecological hazards. Also, there may be, particularly in developed countries, ethical or other social issues raised about the use of transgenic food plants. However, the economic and humanitarian imperatives of their use cannot be ignored. What is critical is that in the implementation and development of the use of transgenic crops, ecological and evolutionary considerations are drawn into the decision making processes at an early stage. This will ensure that appropriate safeguards and management strategies can be devised in parallel with the development and trialing of any transgenic cultivar. With the deployment of biological commonsense and good management practices there will be no need for the stereotypes of ecologists as Luddites and molecular plant breeders as followers of Frankenstein to exist. We as biologists and agriculturalists with a need to address a problem will be able to do so with a reasoned and rational approach for the use of these powerful technologies.