Articles and Notes

Biotechnology: Scientific Potential and Socio-economic Implications for Agriculture

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While genetic engineering has caught public attention, the associated advances in both cell fusion and tissue and cell culture hold more immediate promise for improving agricultural productivity. The potential of these biotechnologies for manipulating micro-organisms, improving plant production systems, improving animal and insect systems, and for industrial tissue culture, is briefly reviewed. The coming Biorevolution in agriculture will have much greater socio-economic impact than the Green Revolution. The distribution of these effects, both within and between countries, will be greatly influenced by private property rights. Biotechnology is not going to be a "quick fix" for the world food problem. Indeed, unless governments can meet the socio-economic policy challenges ahead, the Biorevolution will exacerbate the current paradox of famine in the midst of surplus.

1. Introduction

Recent developments in biotechnology have awakened great public interest and generated widespread debate. Yet biotechnology has been around for a very long time. For millennia humans have used micro-organisms to ferment their wine, beer and yoghurt; subjected their plant and animal resources to selection pressure; and in many other ways employed biotechnologies to manipulate living organisms for their own purposes.

In the early 1970s, however, there was a quantum leap. For the first time humans demonstrated their capacity to manipulate the cellular machinery which controls all living organisms. Advances in molecular and cell biology made it possible to modify or to change individual components within living cells. No longer were humans restricted to working with Nature. They could now create completely new life forms not previously occurring in Nature. These new genetic engineering, cell fusion and associated cell and tissue culture techniques are now commonly referred to as "biotechnology".[1]

As is so often the case in science, the series of spectacular "firsts" during the 1970s which heralded the dawning of the new era of biotechnology, were made possible by a long sequence of basic scientific discoveries spanning at least 150 years. In the early nineteenth century zoologists speculated about the mechanism of heredity. Gregor Mendel's experiments in the 1860s were a major step forward but this experimental evidence remained almost unnoticed until the 1890s. Over the next half century scientists searched for an understanding of the "message sticks of life" or genes which control the characteristics of each and every living thing. By the 1950s DNA had been identified as the substance of which genes are made, and the double helix structure of a DNA molecule had been discovered (Watson 1968). It took almost another two decades before a specific part of the DNA from one organism (a gene) could be deliberately transferred from a parent organism to a new host organism so that the host acquired a new trait due to the expression of the foreign gene.

Public attention has focussed on this genetic engineering aspect of the new technology, but the associated cell fusion and tissue and cell culture techniques which have developed along with genetic engineering are equally significant. In terms of agricultural applications, these associated technologies are likely to be more important than gene splicing, at least for the next decade.

This paper has two objectives. The first is to systematically describe the range of scientifically important and novel forms of biotech-

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1. Strictly speaking these new methods for manipulating cells or parts of cells should be called "new biotechnologies" to distinguish them from the transitional "old biotechnologies" by which whole living organisms have always been manipulated.

nology currently under investigation or being developed for agricultural purposes. Many of these technologies will be in widespread use by the end of the twentieth century. The adoption of these new technologies will have profound implications for the welfare of farm households both in the wealthy industrialized countries and in the Third World. Having established the enormous potential significance of biotechnology for agriculture, the second objective of this paper is to explore the mechanisms by which these technologies are likely to spread around the globe and to examine some of the institutional and socio-economic problems which will arise.

2. Agricultural Applications

The first commercial product of the new biotechnology era was released for sale in September 1982.[2] Currently there are literally hundreds of new biotechnology ("biotech") products and processes being developed around the world and yet the biotech revolution has hardly started. More will be discovered about molecular and cell biology in the next decade than in all of previous history. Biotechnology, therefore, is in its infancy.

No-one can predict what new biotech developments will come on stream in the next 100 years. But, even today, the range of actual and potential agricultural applications is most impressive. By the beginning of the twenty-first century the most amazing of today's biotechnologies will be commonplace in industrial countries and many will have found application world-wide. This paper will concentrate on the current state-of-the-art rather than speculate on what might be around the corner.

Applications of biotechnology to agriculture have given rise to new techniques for manipulating micro-organisms; improving plant production systems; improving animal and insect systems; and for industrial tissue culture.

2.1 Manipulation of Micro-organisms

Since the first successful example of genetic engineering was announced in 1973, the use of recombinant DNA techniques to create new micro-organisms has been one of the most rapidly developing, and most publicized, forms of biotechnology. Less controversial, but equally important, has been the development of new biotechnological processes not only to take advantage of these new engineered microbes but also to utilize more effectively certain naturally occurring but previously neglected micro-organisms. While major advances in molecular and cell biology have made genetic engineering possible, the development of the new biotechnological processes have been greatly facilitated by advances in electronics and chemical engineering.

2.1.1 Genetic engineering of micro-organisms

By taking a single gene from a foreign organism and splicing it into the genetic code of a microbe, scientists can induce the microbe to accept the foreign gene as one of its own and the foreign gene can find expression in the microbial host. These new genetically modified microbes have been used either to produce useful quantities of the natural protein for which the foreign gene is coded or to perform some specific microbiological task which was not possible prior to the insertion of the foreign genetic material.

The manufacture of otherwise rare but naturally occurring proteins has two important but different applications. First, by inserting different genes from the parent organism and observing their expression in the host micro-organism, it is possible to map the genetic code of the parent organism. This technique has made it possible to begin to unravel the gene codes of certain higher plants and animals. This is an essential first step towards the application of genetic engineering to plants and animals.

The second application involves tricking a micro-organism into producing commercial quantities of an extremely valuable but rare natural protein. The pharmaceutical industry has been quick to recognise the potential of this aspect of the new technology. A large number of firms are now developing hormones, vaccines and other substances using genetically engineered micro-organisms. These products will have an extremely high value in human medicine. The veterinary field will also offer very attractive markets for these new products.

Growth hormones have been produced which raise milk production or increase poultry

2. Human insulin made by genetic engineering technology was certified for sale in the U.S.A., Japan and several European countries in September 1982. This date is said to mark the beginning of the commercial exploitation of the new recombinant DNA technology. However the first monoclonal antibody diagnostic kits were approved for use in the U.S.A. in 1981. (Marketing International 1984).

growth rates. Biotechnologically manufactured vaccines are already commercially available for neo-natal diarrhoea in calves and piglets. A vaccine for foot-and-mouth disease is currently being trialled in Argentina. The potential impact of these new products on animal health and productivity will depend upon how well they can compete with existing growth stimulants, vaccines, *etc.* However, in the case of growth stimulants the biotech produced natural protein will be more acceptable to the public (since it is a natural protein and not a synthetic chemical analogue) and in the case of vaccines there may be no alternative (*e.g.* foot-and-mouth disease).

These new biotech substances could substantially lower the cost of producing animals and poultry especially under intensive conditions. In this event these technologies could have a major impact on the relative costs of production of animals under intensive as compared with extensive conditions. A major improvement in the comparative advantage of intensive relative to extensive animal production may have major implications for world trade in meat, coarse grains and other animal feedstuffs.

Genetic engineering has also provided "superior" microbes for certain purposes. For example, new and improved strains of micro-organism have been produced for the digestion of cellulose in ruminants. These microbes have the potential to make ruminant animals like cattle, buffalo, goats and sheep more efficient users of low quality roughages and straw. Another example, this time from the plant kingdom, involves improving the nitrogen fixing capacity of legumes by genetically engineering a better nodule forming bacteria.

2.1.2 Improved biotech processes using micro-organisms

As already emphasised, recombinant DNA technology is not the only form of biotechnology based on microbes which is beginning to have an impact on agriculture. New biotechnological processes are being developed which make previously well known, but uneconomic processes, commercially feasible without using genetic engineering.

The process by which high fructose corn syrup is manufactured is a good example, although this process is almost too old to be classified as biotechnology as the term is used today. Two other examples which have received publicity recently in Australia are SUCROTECH and BIOWASTECH (see Section 2.4.1).

2.2 Plant Improvement[3]

Plant cells can be genetically engineered in much the same way as single cell micro-organisms. The required gene in one organism (not necessarily a higher plant) is isolated and inserted into a vector ("carrier") which then carries the foreign DNA into a host plant cell where it is expressed. If the objective is to obtain a new whole plant, then the host plant cell must be capable of regenerating a whole plant from a tissue culture.

Improvements in tissue and cell culture technology will play a major role in future plant improvement not only because of the need to regenerate genetically engineered plant cells, but also because cell and tissue culture offer major new avenues for plant improvement without gene splicing.

2.2.1 Genetic engineering of plants

The use of recombinant DNA technology to develop superior higher plants has barely begun (Barton and Brill 1983; Board of Agriculture 1984). The major limitation is the lack of knowledge about basic plant biology since each step in the process presents its own difficulties.

Finding the right gene or group of genes is a monumental task, not only because higher plants have around five million different genes (micro-organisms have only about five thousand) but also because not all plant genes are located on chromosomes in the cell nucleus. Some plant genes are located in other components of the plant cell namely chloroplasts and mitochondria.

Another problem arises with multigene traits. By the twenty-first century it may be possible to engineer many traits which result from the expression of a single gene or even a small group of genes. However, commercially important traits in plants such as yield are often controlled by a large set of genes. Finding the scattered genes which determine these multigene traits will be difficult, and developing techniques to manipulate these genes as a package is well into the future.

A further major problem concerns finding an appropriate vector to carry the foreign gene into

3. This section is largely based on Board on Agriculture (1984).

the host plant cell. Fortunately some bacterial plasmids can serve as vectors. In particular the T_i plasmid from *Agrobacterium tumefaciens* (a soil borne bacterium which causes crown gall disease in some plants) is the most promising plant genetic engineering vector so far discovered. The first successful insertion of a foreign gene into a higher plant was announced in 1983 (Board on Agriculture 1984). In this case a bacterial gene for antibiotic resistance was inserted into petunia cells using the T_i plasmid. Whole petunia plants regenerated from the cell culture retained the antibiotic resistance.

This breakthrough created great excitement because it confirmed that genetic engineering was possible for higher plants. But the T_i plasmid will only work for dicotyledonous plants that are susceptible to infection by *A. tumefaciens*. It will not work for monocotyledonous species such as corn, rice, wheat and the other cereal crops. It may be possible to modify the T_i plasmid so that monocotyledons can be infected or it may be possible to find another suitable vector. Until this vector hurdle is overcome, most of the important food crops will not be amenable to recombinant DNA technology.

Even if the correct gene or set of genes can be identified and the vector problem is overcome, there will remain other even more difficult obstacles to the genetic engineering of higher plants. These difficulties include, for example, how to regenerate whole plants from protoplast culture, and how to ensure that the foreign gene is expressed at the right time in the appropriate part of the host plant.

Undoubtedly recombinant DNA technology will be successfully applied to more and more higher plant species over the next decade but it is highly unlikely to have any widespread practical impact on plant improvement until well into the twenty-first century.

2.2.2 Tissue and cell culture

New techniques which make it possible to regenerate plants from cells in culture create the potential for enormous advances in crop improvement in the next couple of decades. Somatic cell genetics, as the new approaches to plant breeding and selection are called, can both increase the genetic variation and greatly increase selection efficiency.

Cell culture takes three major forms. "Protoplast culture", which is the preferred approach in relation to gene splicing, is also used if the aim is to fuse two cells to form a new hybrid cell or hybridoma.[4] So far, only a restricted number of higher plants have been regenerated from protoplasts (Shepard *et al.* 1983).

The most reliable and widely used form of cell culture is "callus culture". A tiny piece of tissue can be taken from an appropriate part of a plant and placed in a solution containing plant nutrients and plant growth hormones. The cells grow and divide and form a lump of undifferentiated cells called callus. This callus can then be transferred to a regeneration medium, containing different combinations of plant hormones, and the callus will differentiate into stems and leaves and then roots grow and a whole new plant develops. Limitless numbers of plants can be cloned in this way from one piece of plant tissue. For more than 20 years, callus culture has been used to clone orchids, and other high value horticultural plants. But it is a costly propagation method and has not yet been used commercially for any agricultural crops.

The third cell culture technique is called "cell-suspension culture". Suspension culture often starts with a piece of callus which is broken up into single cells (or clumps of two or more cells). These individual cells are usually then induced to callus and then regenerated into whole plants. Achieving regeneration from individual cells is extremely difficult. Nevertheless the list of species which can be regenerated from cell-suspension culture and from protoplasts is growing.

Cell culture has unexpectedly created a new source of genetic variation. One would expect that plants regenerated from the same clump of tissue would all be identical but this is not the case. Often the new plants are significantly different from each other and from the parent plant. For reasons unknown, the process of culturing cells can create genetic variation. This has occurred with important agricultural plants such as sugarcane, corn, potato, rice and wheat and many others. Sugarcane plants regenerated

4. A "protoplast cell" is a plant or microbial cell from which the cell wall has been removed. A "hybridoma" is a hybrid cell-line resulting from "the fusion of a normal lymphocyte with a myeloma cell. (Myelomas are tumours of the immune system in which a single lymphocyte line proliferates in an uncontrolled manner.) Following selection and cloning an individual hybridoma line will produce only one type of antibody, a "monoclonal antibody" (Oliver and Ward 1985).

from culture have developed resistance to important pathogens (*e.g.* smut, Fiji virus, and downey mildew). Regenerated corn plants have become resistant to southern corn leaf blight. Cell cultured potatoes have acquired resistance to late and early blight. This process of somaclonal variation has presented plant breeders with an unexpected windfall.

For thousands of years crop improvement has been based on selection for desirable traits. Plant breeding has been laborious and time consuming task since whole plants needed to be assessed in field trials. Cell culture has the potential to ease greatly the task of selection and to speed-up the breeding process. In some cases biochemical agents can be applied to a cell culture to create mutants and/or to identify and to select variants (Chaleff 1983). Since literally millions of cells, each potentially a new plant, can be tested in a single petri dish, the saving in screening labour, time and space would be immense. The problem, of course, is to develop a suitable screening agent. Obviously, a plant trait such as height would not readily lend itself to this approach. On the other hand, resistance to a particular herbicide may be most amenable to this type of selection procedure.

2.3 Improving Animal Production Systems

Mention has already been made of the biotechnological advances with micro-organisms which are already being applied to commercial animal production. Vaccines, hormones, growth regulators and digestion enhancers are currently being developed with the aid of microbes which will have a major impact on animal husbandry.

While genetic engineering via the manipulation of micro-organisms has begun to contribute to raising animal productivity, the direct application of this form of biotechnology to whole animals is still in the experimental phase. Concurrent with the widespread interest in the genetic engineering of higher animals, there has been remarkable progress in the biotechnology required to manipulate animal reproduction cycles. Fertility regulating hormones have been used commercially on animals (including *Homo sapiens*) in many years. It is now becoming feasible to modify other animal cycles in order to increase productive efficiency.

2.3.1 Genetic engineering of animals

Gene transfers between mammalian cells by somatic cell hybridization was achieved in the 1960s and this technique has permitted the mapping of some genes.[5] It is now possible to combine recombinant DNA technology and embryo manipulation techniques so that certain genes from one cell can be inserted into another animal cell. If the foreign gene is to be introduced to all cells of the new organism the host cell must be a fertilized egg cell. Gene transfers of this kind have been achieved with mice, rabbits and other laboratory species and with farm animals such as pigs, sheep, goats and cattle. In some cases, the foreign DNA (or gene material) has been inherited by some of the offspring of transgenic individuals.[6] Unfortunately, however, there have been major difficulties associated with getting the foreign gene to express itself at the right time in the appropriate part of the host animal.

Scientists at the University of Adelaide have recently announced what could be a major breakthrough in this regard. They inserted an extra gene for growth hormone production into pig embryos and one of the resulting pigs has grown 25 per cent faster than its normal siblings.[7] These "super" pigs are more productive because part of their internal hormonally controlled biology has been altered by the insertion of a foreign gene into their genetic make-up. As will be discussed below, some biological cycles which control animal growth and reproduction can be modified by immunization techniques as well. Manipulation of animal hormone systems, either by genetic engineering or by immunization techniques, will soon create major opportunities for the improvement of domestic animal productivity.

5. "Somatic cell hybridization" involves the fusion of two normal cells (*i.e.* not germ cells) to form a new viable cell-line with some or all of the genes from both parent cells.

6. "Transgenic individuals" are animals with genes which have not been obtained from their natural parents.

7. The Adelaide University research team have not only produced a "super" pig, but this animal has also successfully transmitted the foreign DNA to some offspring. (Michalska *et al.* 1986; R.F. Seamark personal communication, March 1987).

2.3.2 Manipulating reproduction

Artificial insemination, which is now widely used for commercial animals, is part of the stock of "old" biotechnology out of which the "new" biotechnology has grown. Embryo transfer technology (especially in bovines) became commercially viable for high-value animals in the 1970s. During the 1980s there have been major developments in regard to *in vitro* fertilization for many species (including *Homo sapiens*). It is now feasible to cryogenically store both male and female gametes, fertilized ova and even partially developed embryos of many animal species for long periods of time. This provides major commercial opportunities for the world-wide marketing of genetically superior livestock and poultry without the transport and quarantine costs of moving the whole animal.

Embryo splitting (a form of cloning or twinning) and sex selection at the embryo stage are two biotechnologies about to become commercially available. Other animal reproduction manipulating technologies being investigated include parthenogenesis (the development of a new individual from an unfertilized egg), cloning (asexual multiplication to ensure all animals in the cloned population have the same genetic make-up) and cloning of inbred animals to provide genetically homogeneous inbred lines preparatory to hybridization (similar, in principle, to breeding hybrid corn).

2.3.3 Modification of animal cycles

The economic production potential of many domestic animals and birds is limited to survival mechanisms inherited from wild ancestors. For example, many animals and birds adjust their fertility and growth rate according to changes in day-length (or other seasonal phenomena). Relatively simple biochemical pathways control some of these inherited responses. As more is learned about hormone growth factors, immune regulators and neurological peptides it is becoming increasingly possible to interfere with natural biochemical pathways controlling these economically important animal cycles.

For example, it has been shown that a single enzyme can block the biological process by which goats close down the mohair producing cells in their skin when day-lengths begin to shorten.[8] Goats which can be induced to produce mohair all-year-round grow 30 to 40 per cent more of the valuable fibre, yet require no additional feed.

Another potential application of this approach to improving animal production involves lowering the basal metabolic rate and hence maintenance feed requirements. Large animals could be biologically "turned down" during droughts, thus conserving scarce feed supplies.

As mentioned above, animal cycles can be manipulated both by genetic engineering of the animal and by immunological techniques. While the latter approach may be closer to widespread practical application, both techniques have the potential to revolutionize animal husbandry in the twenty-first century.

2.4 Industrial Tissue and Cell Culture

Perhaps the biotechnology which will have had the most profound impact on world agriculture over the next decade is tissue and cell culture. Microbial cell culture is an "old" biotechnology which has received a major fillip from the recent interest in genetic engineering. New ways of manipulating well known microbial processes, such as fermentation and single cell protein production, are being developed in many parts of the world with and without genetically engineered microbes.

But it is the recent advances in the culturing of large numbers of undifferentiated plant or animal cells which have created a wide range of new applications. These cultures can be used for diagnostic purposes, for screening new drugs, or for the direct production of valuable substances. A major breakthrough with this type of biotechnology occurred when the first hybridoma was created in 1975. Recently, certain cancer cells have been fused with specialized cells from the mammalian immune system. This process has produced a hybridoma cell line with the immortality and rapid proliferation traits of the cancer cells and the capacity to produce large quantities of what are referred to as monoclonal antibodies. These antibodies can be used for the diagnosis and treatment of diseases in animals and humans and for the purification of proteins.

8. Dr. B. Norton, Department of Agriculture, University of Queensland (personal communication).

2.4.1 Microbiological cultures

Pharmaceutical companies have been using micro-organism cultures to produce antibiotics and other useful medicines for both medical and veterinary purposes for over 30 years. These commercial laboratories were quick to perceive the potential of the new genetic engineering techniques for broadening the range of products available to the pharmaceutical industry. The sudden interest and investment in genetic engineering research and development (R and D), both by large traditional pharmaceutical companies and by many hundreds of smaller new biotech firms established since the late 1970s, has re-awakened commercial interest in the production of industrial materials by microbial means (Marketing International 1984).

The market for industrial products based on microbial fermentation processes (*e.g.* beer, spirits, cheese, bread, cider, yoghurt, wine, sewage treatment, silage) is much larger than the market for pharmaceutical products. For example, Dunnill (1983) noted that the total sales of all pharmaceutical products in the United Kingdom in 1980 was only about one quarter of the value of industrial fermentation products. The situation would be similar in other advanced countries, with the relative economic importance of industrial fermentation being even greater in most Third World countries. On a world-wide basis, therefore, there is enormous potential for new biotechnological processes to revolutionise traditional industrial fermentation (Knorr and Sinskey 1985).

There is also scope for the emergence of completely new industrial products based on biotechnology. Reference has already been made to one of the most successful new processes of this type, namely the enzymatic digestion of corn starch to obtain high-fructose corn syrup (HFCS). Commercial production of HFCS began in Japan in 1967 and spread to the U.S.A. in 1972 (Casey 1976). In little more than a decade, this new industrial process has become a serious threat to natural sugar. Sugar has now lost almost half the U.S.A. sweetener market and at least 10 per cent of the world sweetener market. This new industrial product based on biotechnology has, therefore, been a major factor depressing the world price of natural sugar. Low sugar prices are currently a serious problem for many Third World economies which have traditionally relied on sugar exports.

One possible solution for these nations may be to follow the Brazilian example and use sugarcane as a feedstock for the production of ethanol. The traditional yeast fermentation process for producing ethanol has been improved but remains uneconomic without massive subsidies, given the current and likely future prices of petroleum. However, a new biotech process promises to lower significantly the cost of producing ethanol from sugar cane and to produce fructose at the same time. This process, patented under the name of SUCROTECH, is now being commercially marketed. Ironically, this new approach to making ethanol also has the potential to produce fructose from sugarcane cheaply enough to undercut HFCS and regain the world sweetener market for cane growers (Doelle and Greenfield 1985a,b,c; Fuelling 1985).

Single cell protein manufacture based on sewage, feed-lot effluent or other suitable substrate of low value, has always had the potential to provide a major protein source, especially as an animal feed (Litchfield 1983). The problem has always been the low productive efficiency and hence high cost of microbial protein manufacture. A new biotechnology (patented as BIOWASTECH) has been developed which converts piggery wastes, human sewage and other low cost "problem" substrates into high quality protein virtually equivalent to soybean meal. This technology is remarkably simple and can be adapted for village level application in Third World countries.[9]

World-wide application of processes such as SUCROTECH and BIOWASTECH would have dramatic implications for some existing industries. A process like SUCROTECH, which efficiently converts sugarcane to fructose and ethanol *at the same time*, obviously has the capacity to rescue natural sugar by making it an industrial raw material. This would be good news for many Third World countries. On the other hand, the U.S.S.R., Japan and other major importers of other major importers of protein rich animal feedstuffs may find improved single cell protein manufacturing processes like BIOWASTECH can greatly reduce their need to import commodities such as soybeans, peanuts *etc*. Plant protein exporting countries such as Senegal, Brazil, Argentina, U.S.A. and Australia would be the losers.

9. Dr. D.P. Henry, Waste Utilization Research Unit, University of Queensland (personal communication).

2.4.2 Plant cell and tissue cultures

In principle, any known plant product (and, indeed, many currently unknown plant compounds) can be produced by plant cell and tissue culture techniques (Staba 1980). Given the present relatively high cost of plant culture technologies, the choice of potentially commercially viable industrial cultures depends upon the availability, quality and cost of competing sources of the end product. Single compound substances with a high commercial value but which are only available from a few relatively unreliable sources, and which are difficult or impossible to synthesise by chemical means, have been the major targets to date (*e.g.* opium, digitalis and pyrethrin). However, more complex substances often involving several chemical compounds (*e.g.* food flavourings such as capsaicin which is the major component in chili peppers) are also being produced by tissue culture techniques (Jones 1983).

Large scale industrial interests have already identified about thirty plant substances which have a very high value and a small volume market and which could be produced by plant cell and tissue culture technology. Many of these substances are specialty plant products (*e.g.* pyrethrin) which represent a major proportion of the income of small scale farmers in those few areas of the world where the product can be grown naturally. Although the naturally grown substance may be cheaper at present, industrial manufacture by biotechnological means has many advantages from the viewpoint of the end-user. Plant cell and tissue culture could become a major new industry by the beginning of the twenty-first century. Indeed, it is the kind of technology which would be well suited to the new agro-technology parks being planned by land scarce countries such as Singapore.

One exception to the high-value/low-volume specialty substance rule is tobacco. Both in Japan and in Europe there has been substantial investment aimed at developing tobacco cell culture to the point of commercialization. There may be major market distortions, due to political factors or the lack of foreign exchange in some countries, which could make tobacco cell culture cost-effective. In general, however, it is not likely that any major plant product which is relatively freely traded internationally will be replaced by the culturing of individual cells rather than the whole plant.

Plant cells in culture require a substrate. The substrate can only come from one of two sources, that is, either from agriculture or from fossil fuel. Irrespective of the source, the substrate provides energy, which was originally photosynthetically fixed solar energy, to drive the biotech process. Only about half the carbon in the substrate is converted into biomass. In purely physical energy terms, whole plants capable of photosynthetically capturing freely available solar energy, will always be potentially more efficient manufacturers of plant products than plant cell and tissue cultures in bio-reactors. Whether plants, and the farmers who grow them, are permitted to continue to exercise their comparative advantage remains to be seen.

2.4.3 Animal tissue and cell culture

In vitro fertilization for the improvement of animals involves culturing animal cells. The growth of animal cell cultures for disease diagnosis and for screening potential drugs is also now a common practice in pathology and pharmaceutical laboratories around the world. Experience and knowledge gained in culturing animal cells for these purposes has given rise to a major new industry. The potential now exists for the production of many animal enzymes, hormones, antigens *etc.* by culturing animal cells directly rather than by extracting the relevant gene and inserting it into a microbe. Human insulin, for example, the first commercially available product of genetic engineering could, in principle, now be obtained by this means thus eliminating the need to rely on genetically engineered microbes.

3. Implications for World Agriculture

How rapidly the technologies outlined above begin to affect world agriculture, and how these effects (both positive and negative) are distributed across countries and even more importantly, within countries, will be of profound significance. The Biorevolution will be a logical extension of the Green Revolution which began in the late 1960s but it has the potential to have a much greater impact on world agriculture than the Green Revolution (see Table 1).

The Green Revolution has transformed a significant proportion of world agriculture over the last two decades (Per Pinstrup-Andersen

Table 1: Comparison of the Characteristics of the Green Revolution and the Biorevolution

Characteristic	Green Revolution	Biorevolution
Crops affected	Primarily wheat, rice, maize	Potentially all crops, including horticultural crops (*e.g.* vegetables, fruits,) agro-processing crops (*e.g.* rubber, oil palms, cocoa), and specialty crops (*e.g.* spices, scents)
Non-crop products affected	None	Animal products Pharmaceuticals Processing food products Energy
Locations affected	Some locations in some less developed countries (*i.e.* if accompanied by irrigation, high quality land, transport availability, *etc.*) Most developed countries especially in the case of wheat.	All nations all locations including marginal lands (characterized by drought, salinity, aluminium toxicity, *etc.*)
Technology development and dissemination	Largely in the public or quasi-public sector	Largely private sector (transnational corporations and new biotech firms, with the former predominating in terms of commercialization)
Proprietary considerations	Patents and plant variety protection generally not relevant	Processes and products patentable and protectable
Capital costs of research	Relatively low	Relatively high
Research skills required	Conventional plant breeding and parallel agricultural sciences	Molecular and cell biology expertise plus conventional plant breeding skills
Resources displaced	None (except the germplasm resources represented in traditional varieties and land races)	Potentially any

Source: based on Kenney and Buttel (1985, p.70).

and Hazell 1985). While the Green Revolution was initially restricted to wheat and rice, new high yielding varieties (HYVs) are now available for a broad range of crops. These HYVs, together with their associated package of new inputs, have now been widely adopted in Third World countries and they have greatly increased productivity and farm incomes in those areas to which they are suited. Not only have the farmers benefited but also the increased production has lowered food prices for urban workers and increased national food self-sufficiency. Economic development has received a major boost in many countries.

On the negative side, the Green Revolution has made many Third World farmers more dependent on factor markets; it has often created a worsening of rural income distribution since not all farm households can take advantage of the new technology; and it is often blamed for the displacement of rural labour by mechanisation. Third World agriculture has become more capital and energy intensive, and hence more subject to economic and financial risks. The Green Revolution has also reduced genetic diversity at the farm level and thus potentially heightened the risk of world-wide famine (akin to the Irish potato famine).

The Biorevolution will build on the accomplishments of the Green Revolution (Kenney and Buttel 1985). Its effects, however, are likely to be more widespread in that potentially all plant and animal production systems could be affected (Buttel *et al.* 1985). The distribution of the benefits and costs of the new biotechnology will depend largely on which of the potential technologies receives the greatest emphasis both on a world-wide scale and within each individual country.

The implications of biotechnology for world agriculture, therefore, may depend as much on social and economic policy choices over the next two decades as on scientific progress.

3.1 Organizing Agricultural Research

In contrast to the public investment in research which created the Green Revolution, the R and D required to make the Biorevolution in agriculture happen has, so far, been overwhelmingly financed by private investment (Marketing International 1984). Initially, the transnational companies (TNCs) in the pharmaceutical and petrochemical industries began to expand their biotechnology R and D budgets. These moves were rapidly followed by TNCs in the food processing, grain marketing, seed production and general engineering industries. These large companies have recognised that a strong synergistic relationship now exists between R and D in agrichemicals, biotechnology and seed production. The result has been a world-wide rush to take-over small specialist seed producing companies. Plant variety rights legislation in the U.S.A. and elsewhere has also encouraged these moves towards greater concentration in the agribusiness world.

While the large TNCs have been jostling for a better position in the biotechnology race, there has also been a rush of new venture capital into the field (see Table 2). New biotechnology firms (NBFs) have proliferated rapidly, especially in the U.S.A. but also in other countries. These NBFs have often been set up by one or more individual biotechnology scientists, or have hired such scientists, to scale-up and commercialize a specific biotechnology. Both these NBFs and the traditional TNCs have also entered into contracts with university departments for biotechnology research. This worldwide commercial interest in biotechnology represents a consensus about the ultimate impact and value of biotechnology.

National governments both in developed nations and in less developed countries have encouraged biotechnological research. Indeed it has even been suggested that some countries, such as Japan, have given their biotechnology firms so much encouragement that they have an

Table 2: Major Events in the First Decade of Commercialization of Biotechnology

1973	• First gene cloned.
1974	• First expression of a gene cloned from a different species in bacteria. • Recombinant DNA (rDNA) experiments first discussed in a public forum (Gordon Conference).
1975	• Guidelines for rDNA research outlined (Asilomar Conference) in the U.S.A. • First hybridoma created.
1976	• First corporation established specifically to exploit rDNA technology established in the U.S.A. (Genentech). • Genetic Manipulation Advisory Group established in the United Kingdom.
1980	• U.S.A. Supreme Court rules that micro-organisms can be patented under existing law. • Cohen/Boyer patent issued on the technique for the construction of rDNA. • United Kingdom targets biotechnology (Spinks' report). • Federal Republic of Germany targets biotechnology (Leistungsplan). • Initial public offering by Genentech sets Wall Street record for fastest price per share increase ($US35 to $US89 in 20 minutes).
1981	• First monoclonal antibody diagnostic kits approved for use in the U.S.A. • First automated gene synthesizer marketed. • Japan targets biotechnology (Ministry of International Trade and Industry declares 1981 "The Year of Biotechnology"). • France targets biotechnology (Pelissolo report). • Initial public offering by Cetus sets Wall Street record for the largest amount of money raised in an initial public offering ($US115 million). • Industrial Biotechnology Association founded. • DuPont commits $US120 million for life sciences R & D. • Over 80 NBFs had been formed by the end of the year.
1982	• First rDNA animal vaccine (for colibacillosis) approved for use in Europe. • First rDNA pharmaceutical product (human insulin) approved for use in the United States and the United Kingdom.
1983	• First plant gene expressed in a plant of a different species. • Over $US500 million raised by new biotechnology firms in U.S.A. capital markets.

Source: based on Marketing International (1984, p.4).

unfair advantage. As far as Japan is concerned, the facts seem to refute this suggestion, at least in comparison with the U.S.A. (Saxonhouse 1985). Nevertheless, biotechnology research and development is currently largely under the control of private firms owned predominantly by American, Japanese or European interests.

Most less developed countries have recognised the potential of biotechnology for both industrial and agricultural development. Some, like India and the Philippines, have set up national institutes for biotechnical research (Swaminathan 1982). The United Nations Industrial Development Organisation (UNIDO) has been endeavouring to establish an International Centre for Genetic Engineering and Biotechnology. The UNIDO sponsored centre would combine the financial resources of Third World countries so that a worthwhile biotechnology R and D program could be mounted to serve the needs of the less developed countries. Such a centre could facilitate the transfer of biotechnology to the Third World and reduce the risks associated with depending on TNCs for access to the latest technology (Kenney and Buttel 1985).

Green Revolution technology was comparatively inexpensive to develop and, for the most part, it was created at public institutions especially the International Agricultural Research Centres (IARCs) now controlled by the Consultative Group on International Agricultural Research. These IARCs initially drew heavily upon the universities and other agricultural research institutions in the advanced countries and especially on the U.S. Land Grant universities and the U.S. Department of Agriculture's Agricultural Research Service for staff, ideas and, in the case of plant breeding, germplasm. Green Revolution technology was made freely available, through the IARCs, to public development programs and government agencies in the less developed countries.

The Biorevolution in agriculture will not spread through the same channels. While some of the IARCs are attempting to support biotechnology research programs, these centres are faced with tight budgets which scarcely permit the maintenance of traditional research programs.

Furthermore, Land Grant universities in the U.S.A. and agricultural universities in other countries (the parent institutions to which the IARCs have traditionally turned for staff and basic research support) are not in the forefront of biotechnology research (Buttel *et al.* 1984). Public funding at these universities has been restricted for more than a decade and resources have not been available, in most cases, to begin expensive biotechnology research. Private funding and contracting for biotech research has tended to be directed to the basic science departments in the large private universities in the U.S. or to newer high-tech centres such as Tsukuba University in Japan.

Recognising the start which private companies have in the biotechnology race, it would probably be unwise for Third World nations to expect their publicly funded universities and research institutions to bridge the gap. The only practical policy may be the vigorous encouragement of joint R and D ventures between overseas high technology companies and domestic researchers both in public and private institutions. For example, the Thai Government is planning to establish a Oil Palm Research Institute at the Prince of Songkla University on the eastern side of the southern Thailand peninsula. The chances of this Institute making a worthwhile contribution to the future of the hard pressed Thai oil palm industry are slim unless it can acquire access to the technology and knowledge bank available to the TNC (Unilever) currently developing palm oil plantations at Trang and Krabri on the western side of the southern Thailand peninsula.[10] This is a clear case of the long-term national interest being better served by the public sector joining forces with the TNC rather than trying to go it alone. Governments and research institutions in the less developed countries will need to work with private companies if they are to gain access to the biotechnology which will fuel the emerging Biorevolution in world agriculture.

3.2 Patents, Plant Variety Rights and Biorevolution

In 1980 the U.S. Supreme Court ruled that micro-organisms can be patented under existing law (Table 2). Almost all the advanced countries and many less developed nations now have

10. The oil palm plantations at Trang and Krabi are being established using the latest genetic material and the latest cloning technology developed in the R & D laboratories of Unilever. (Mr. J.P. Evenson, Faculty of Natural Resources, Prince of Songkla University, Hatyai, Southern Thailand, personal communication.)

plant breeders rights or plant variety rights legislation in place. The biorevolution, therefore, will be based on seeds, processes and konwledge which are private property (Kloppenburg and Kenney 1984). The decisions as to which germplasm to release, which vaccine to market, which processes to incorporate in new biotech factories *etc.*, will be tempered by commercial considerations. Countries which for one reason or another are not commercially attractive may find the Biorevolution in agriculture passing them by.

As the agricultural sector and its economic development largely determines the rate of progress in almost all LDCs, the private capital intensive basis of the Biorevolution in agriculture will present many LDC governments with some difficult policy choices. Farm households will become increasingly dependent on factor markets and, if the factor markets are to supply these farmers with the latest available biotechnologies, then governments will need to permit TNCs and their agents to operate in these markets. The same will apply to many agricultural product markets especially if the product is a raw material for a biotechnological industry. For LDC governments to permit, indeed to actively encourage, such privatization of the agribusiness sector by TNCs will be seen by many as "turning-the-clock-back". Yet there may be no feasible alternative if such governments want their agriculture sector to participate in the Biorevolution.

3.3 The Global Village and the World Food Problem

Modern communications and transport have shrunk the world and greatly increased interdependence between nations. Yet there are two contradictory food problems facing the world today. The advanced nations and the agricultural exporting countries in the Third World are troubled by over-production and poor prices for farm products. At the same time, many millions of people in some countries and even the whole population in a few nations, face chronic malnourishment and even famine. When it comes to distributing the available food, the world certainly is not a global village.

Biotechnology will not resolve this paradox. Indeed, unless the necessary international and, in many cases, national political and social reforms are introduced to alleviate world hunger, the coming Biorevolution will exacerbate the situation. The new biotechnology will be made available and will be adopted most rapidly where there is a commercial incentive. It may even increase world food surpluses but do little *directly* to help the subsistence farmers and herdsmen of Africa feed their families.

Biotechnology wil not be a "quick fix" for the current "shortage in the midst of surplus" world food situation. The coming Biorevolution will exhibit much the same positive and negative features as the Green Revolution. Furthermore, these opportunities and problems will affect more of world agriculture than has been the case with the Green Revolution. Governments have been slow to capitalize on the enormous social benefits of the Green Revolution and quick to highlight the social costs. Ultimately, the value of the coming Biorevolution will depend on the capacity of social and political institutions to adjust to the enormous changes in world agriculture which will occur in the twenty-first century (Fishel and Kenney 1985).

4. Conclusions

The biotechnology revolution in agriculture has only just begun. By the turn of the century virtually every facet of agriculture will have been influenced by the emerging new biotechnologies. Not all of these developments will find ready adoption. There will be a major technical, economic and political constraints which will retard the spread of the new technologies (Feder, Just and Zilberman 1985).

Nevertheless, there is a certain inevitability about science. Once some major breakthroughs are achieved, myriads of applications follow. Certainly there have been major breakthroughs in biotechnology in the last fifteen years. These advances have already found application in agriculture and undoubtedly there are many more in the pipe-line.

World agriculture has grown accustomed not only to heavy public investment in the development of new agricultural technology but also to a high degree of public control over the extension/adoption process which has dispensed this technology free to farmers. Much of the new biotechnology for agriculture is being developed by private firms which will want to market their discoveries to farmers at a profit. The implications of biotechnology for agriculture, therefore, can not simply be discussed in terms of the potential for increasing produc-

tivity or creating new products. The coming Biorevolution will provide a hitherto unprecedented upheaval in the economic, social and political structure of world agriculture. The ultimate value of biotechnology to agriculture will largely depend on the capacity of governments to develop policies to cope with these economic, social and political changes.

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