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COMMENTARY

Transition to Twenty-First Century Agriculture: Change of Direction

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Abstract Agriculture of the twentieth century will be remembered for its scientific foundations and for high crop yields. The transformation began following a number of scientific discoveries which modernised agriculture and gave rise to intensive production systems. A major break-through came in the second half of the twentieth century with the discovery of new plant-type genes in wheat and rice, which were instrumental in giving rise to the green revolution. The high-yield agriculture, as it has evolved with the advent of the new technology, calls for large investments of energy in the form of fossil fuels. Agriculture in the twenty-first century will have to respond to challenges of a different kind. Perhaps the most important consideration in the planning of agricultural research in the coming decades will be the need for a much greater focus on the sustainability of intensive production systems, environmental and efficiency concerns, equity, and management of natural resources. Fortunately, continued advances in molecular biology, biotechnology, information technology, nano-technology and space science offer altogether new opportunities for making agriculture not only highly productive but also more efficient and sustainable in relation to the use of natural resources and modern farm inputs. As the twenty-first century advances, we may come to have a different kind of agriculture combining high-crop yields with management practices based on renewable resources of energy. The scientists will be moving away from a single minded pursuit of genetic improvement to greater focus on development of new resource conservation and precision farming practices.

Keywords New plant type genes · Agriculture in twenty-first century · Genetic improvement · Rubisco · Resource conservation

Agriculture of the twentieth century will be remembered for its scientific foundations and for high crop yields. The change began following a number of scientific discoveries which were to modernise agriculture and give rise to intensive production systems. Darwin [4] had put forward his theory of origin of species in 1859 with a totally new concept of the biological world. It took time for the theory to gain wide acceptance and once that happened, its implications for the evolution of improved crop varieties and new breeds of animals were not lost. Mendel's [11] laws, which led to the concept of genes as determinants of different traits of an organism and an understanding of their mode of inheritance, provided the needed scientific methodology for this purpose. Liebig's [10] work about the same time on the role of inorganic fertilizers in crop production provided a new insight in the field of plant nutrition, and Muller's [12] synthesis of DDT paved the way for the use of a large number of organic pesticides for crop protection.

As the new technologies were adopted by the farmers, crop yields started to register a steady increase in many industrialised countries including Japan and Australia. Heady [6], writing on the agriculture of the United States, has recorded that between 1910 and 1970, the output of American agriculture approximately doubled with a reduced acreage. Heady makes the point that this happened when the government created a new capital resource in the form of scientific knowledge, with the new agricultural

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technology replacing the earlier policy of land expansion. In Europe too, the transition to a more modern agriculture based on the new scientific discoveries was well on its way.

The Green Revolution

Even as progress was being made in increasing crop yields, a break-through came in the second half of the twentieth century with the discovery of plant-type genes in wheat and rice, the food staples of people in most parts of the world. The term green revolution [7] has been widely used to describe the impact of these new technologies based on high-yielding varieties and heavy use of modern farm inputs.

New Plant-Type Genes in Wheat

Farmers in Japan had identified a landrace of wheat which they called Daruma. It was Daruma whose dwarfing genes were to become an important genetic resource for the development of high-yielding varieties of wheat all over the world. Once Daruma came to the attention of wheat breeders in Japan, they started to use it as one of the parental lines in their hybridisation programme. Their main objective was to develop short-stratured stiff-strawed varieties of wheat which will take full advantage of the application of large doses of inorganic fertilisers and irrigation. The traditional tall varieties of wheat under such conditions had tended to lodge. A semi-dwarf high-yielding variety of wheat they developed from these crosses was named Norin-10, which was to acquire a cult status among wheat breeders. Shortly after World War II Norin-10 was introduced in USA, where Vogel et al. [15] at the Washington Agricultural Experimental Station, Pullman used it in one of his crosses to develop a new winter wheat variety called Gaines, which is reported to have registered a record grain yield of 14 tonnes per hectare under high fertility conditions. Following the success of this winter wheat variety, the Norin-10 dwarfing genes were successfully placed into the genetic background of spring wheats by Borlaug [1] at CIMMYT in Mexico, and subsequently by breeders in the national institutions of major wheat growing countries. This was to mark the beginning of a wheat revolution in countries like India, Pakistan, Turkey, Mexico and in many other countries, where spring wheat is an important food crop.

New Plant-Type Genes in Rice

In parallel with wheat, the second half of the twentieth century saw the beginning of a rice revolution. It all started with a traditional variety called Dee-geo-woo-gen, which farmers in Taiwan were found to be growing in the early years of the twentieth century. For an indica rice variety Dee-geo-woo-gen was very different in its plant-type, showing dwarf stature, high tillering and stiff straw. Much later, this farmers' variety came to the notice of scientists at the Taiwan Agricultural Experiment Station. Impressed with its plant architecture, they started using it in their breeding programme in the 1950s to develop fertilizer responsive high-yielding varieties of indica rice. One of the products of their crosses was the variety Taichung Native 1, perhaps the first semidwarf, fertilizer responsive, high-yielding rice variety developed through scientific breeding, which in later years became the prototype of a whole new generation of indica rice varieties in many countries of Asia. The spread of these new plant-types in rice was made possible with the efforts of the scientists at the International Rice Research Institute in the Philippines who used these semi-dwarf varieties of Taiwan origin extensively in their breeding programme and came out with a series of new high-yielding indica rice varieties starting with IR-8. The new varieties developed at IRRI [9] and in the research institutions of many Asian countries had a major impact on production in the rice growing countries of south and south-east-Asia and in other parts of the world.

The high-yielding varieties of wheat and rice developed in the second half of the twentieth century helped to overcome serious food shortages in many developing countries. Never before perhaps had application of science made so much positive impact on the lives of so many people. As for the developed countries they began to face problems of a different kind with continued advances in their agricultural production. Heady [6] reported that more than a third of all the wheat grown in USA was exported in 1965. Many of the West European countries too had to contend with problems of farm surpluses which came to be known as the butter mountains.

A Highly Productive but Subsidised Agriculture

With all these advances in the production and productivity of agriculture in the industrialized countries, and in more recent years in some of the developing countries, can we truly say that modern agriculture has proved to be an unqualified success? It is now widely recognized that the high-yield agriculture, as it has evolved since the second half of the twentieth century with the advent of the green revolution technology, calls for large investments of energy in the form of fossil fuels. Pimentel [13] analysing the energy input and output has pointed out that the harvested food grains in the U.S. agriculture provide half the amount of energy invested in their production. Stout [14] has reported on the large investments of energy in the agriculture of European countries. Thus, modern agriculture as practiced in the industrialized countries may be highly productive but it has not been biologically efficient when we consider these huge investments of energy. The high energy-input led agricultural production systems are now been followed in many developing countries to feed their growing populations, even when they find it hard to offer large farm subsidies of the kind available to farmers in the European Union.

Challenges of the Twenty-First Century

Agriculture in the twenty-first century will have to respond to challenges of a different kind, some of which are considered here.

Sustainability of Production Systems

Perhaps the most important consideration in the planning of agricultural research in the coming decades will be the need for a much greater focus on the sustainability of intensive production systems. The present agricultural technology associated with the green revolution is based on a simple paradigm of favourable genotype-environment interactions. The semi-dwarf varieties of crop plants with a high harvest index thrive in a highly manipulated agronomic environment dominated by the use of chemicals of various kinds. There are serious concerns about the long-term viability of some of these technologies.

These concerns arise from the fact that with the development of irrigation, vast tracts of agricultural lands have been lost to crop production because of increasing salinity associated with poor drainage. Also, there has been large-scale mining of soils, leading to deficiencies of plant nutrients like zinc and boron. The wheat-rice rotation that in recent years has become the fundamental basis of food security in much of South Asia continues to present serious problems of long-term sustainability; many of the high-yielding varieties no longer show the kind of productivity they did in earlier years. Scientists at IRRI have observed that some of their modern varieties of rice show a declining trend in yield, even with high input use. There is no reason to believe that their genetic potential for productivity has deteriorated, but apparently soil conditions following intensive cropping over a number of years no longer provide the kind of favourable conditions for crop growth that they did in the earlier years.

The United Nations Report entitled “Our Common Future” defined sustainable development as the new paths of progress that meet the needs and aspiration of the present generation without compromising the ability of future generations to meet their own needs. This concept of sustainable agriculture development is realistic, even if one could argue that it suggests a certain arrogance on the part of humankind. We seem to be saying that we have every right to increase our population as much as we like even though the need for high birth rates is no longer justified because of greatly reduced child mortality. And our food habits will continue to be determined not by scientific considerations of what constitutes balanced nutrition, but by our cultural preferences. *Homo sapiens* is the only species that makes such unreasonable demands on nature and natural resources.

Environmental and Efficiency Concerns

The intensive use of chemicals in modern agriculture is also responsible for major environmental problems. There has been a build-up of nitrates in the rivers and lakes, which are the sources of our drinking water supply. There are also other environmental ill-effects, such as the contamination of foodstuffs with residues of pesticides and toxic chemicals.

The evolution of the high-input technology started during a period when fossil fuels were readily available, and energy was not a major constraint. No one was seriously concerned in the early years of the twentieth century with the efficiency of the agricultural production process, and only a few estimates were made of the energy input/output ratio in different systems of agricultural production. It is only now, following the oil crisis of the 1970s and with the crude prices rising again that scientists are beginning to focus on the issue of efficiency. Western Europe uses the largest amount of energy in its agriculture, followed by North America, with Africa using the least.

One response to this concern about the environment has been a call that world agriculture should revert to its traditional methods with major emphasis on recycling of organic wastes and residues for meeting the nutrient needs of crop plants. While the use of organic manures along with inorganic fertilisers is highly recommended, the option of low-input agriculture no longer exists. The traditional system of farming with all of their professed virtues are based fundamentally on low crop yields. They were a compromise between low productivity and small human populations kept in check by disease epidemics. All this has changed with human populations continuing to rise in countries of South Asia and sub-Saharan Africa. More than ever before, the need now is to increase productivity per unit of land, and all possible resources of modern science must be harnessed to achieve this objective. The solutions to our emerging problems will not be found in low-input agriculture.

Production, Equity, and Management of Natural Resources

The scientific challenge is the generation of a new kind of production technology for the vast dry and marginal lands, which so far have received relatively little attention. It is known that the key to improving the productivity of these lands lies in the rehabilitation and restoration of their soil fertility and in the conservation and management of rain water so that enough moisture is available to provide the equivalent of one or two protective irrigations. Once enough of this water is conserved to sustain some of the critical stages of crop growth, the high-yielding varieties already developed could be introduced in these lands with the application of moderate doses of inorganic fertilisers.

New Scientific Solutions

Agriculture of the twentieth century derived powerful support from landmark scientific discoveries as discussed above. Science once again must help to find solutions to the agriculture of the twenty-first century. Fortunately, continued advances in molecular biology, biotechnology, information technology, nano-technology and space science offer altogether new opportunities for making agriculture not only highly productive but also more efficient and sustainable in relation to the use of natural resources and modern farm inputs.

Improved Photosynthetic Efficiency

The ability of green plants to synthesize food from atmospheric carbon dioxide and water, with solar radiation providing the energy for the process, sustains mankind and, indeed, all living organisms. The first thoughts, therefore, always focus on improving the efficiency of this key biological process. Crop physiologists have not found a significant variation in the rates of photosynthesis in most plant species. The reason for this is attributed to the key enzyme involved in photosynthesis, ribulose-1,5-bisphosphate carboxylase-oxygenase, commonly called Rubisco. The enzyme acts at a low efficiency primarily due to its poor turnover rate for carbon dioxide fixation. Secondly, Rubisco catalyses two different functions, that of fixing CO_2 to produce carbohydrates, and that of the process of photorespiration, when some of these products are lost. Plant leaves accumulate large amount of this enzyme to make up for its low turnover rate, so much so that Rubisco has been described as the single most abundant soluble protein on the earth.

Evolution of Rubisco

Those of us who expect higher turnover rates from Rubisco have to remember that the enzyme is the product of an evolutionary process going back some 3 billion years when this protein first appeared in bacteria. Over this very long period, the Rubisco protein would have seen many changes following random gene mutations and selection pressures for adaptation to changing environments, especially in terms of the concentration of CO_2 and O_2. Natural selection which shaped Rubisco over millions of years was not directly concerned with its efficiency in fixing carbon dioxide. Only that variation would have been selected which contributed to the fitness of the organism through adaptation to varying environments and our present Rubisco is a product of this kind of selection pressures, not those for high crop yields.

C_3 Systems

Rubisco characterizes the most common photosynthetic system in plants called the C_3 system, which is considered to be relatively inefficient in making use of higher light intensities for CO_2 fixation. There is another photosynthetic system called the C_4 observed in many grasses including crop plants like maize, sorghum and sugarcane, which is more efficient in fixing carbon dioxide as long as solar radiation and water are not limiting factors. The C_4 system has evolved not as a substitute for the C_3 system but to partly bypass it. The trick here is that in this system a different enzyme phosphoenolpyruvate carboxylase is involved, which initially fixes CO_2 in the outer mesophyll cells of the leaf. This enzyme has a greater affinity for CO_2 and thus does a better job than Rubisco in carbon fixation. Having fixed large amount of carbon into C_4 compounds, the new enzyme retires and Rubisco takes over carrying out the rest of the photosynthetic process in its usual way. Fortunately, the C_4 plants also lose less of their carbohydrates through the process of photorespiration, possibly because, as Cooper [3] has pointed out, any CO_2 produced is refixed before it can escape through the leaves.

DNA Technology

Randomly occurring mutations and natural selection can do only so much and it is clear that Rubisco will remain what it is, if left to the forces of natural selection. This is where modern DNA technology may have a contribution to make in the twenty-first century. All the genes involved in the process of photosynthesis have to be identified and cloned, their functions understood and mutant alleles produced. It is well to remember that the total biochemical machinery of photosynthesis is made of several different components, which may have evolved independently, and which at some point of time came together. This kind of capturing of genetic information from diverse sources is known to occur in nature and it offers hope for reassembling of the different components of photosynthesis in the interest of greater efficiency of Rubisco. Clearly, this is a huge challenge in the field of genetic engineering. But the rapid progress which has been made is beginning to catch the imagination of molecular biologists and a great deal of research to convert C_3 crop plants into C_4 is currently in progress.

Biological Nitrogen Fixation

Fertilizers account for nearly 50% of energy input in modern agriculture, and of these, fertilizer nitrogen receives high priority. If we were to identify one factor which characterizes modern agriculture making it different from traditional, it will have to be the application of large doses of fertilizer nitrogen. Molecular nitrogen (N_2) is abundantly available in the atmosphere, but somewhere in the course of their evolution from bacteria, plants and other organisms lost the DNA sequences coding for the ability to fix molecular nitrogen. The nitrogenase complex enzyme catalyses the transformation of molecular nitrogen into ammonia that becomes available for plant growth as fertilizer.

Synthetic fertilizer nitrogen became available for agriculture in the early years of the twentieth century following the development of the Haber–Bosch industrial process for the production of ammonia. So how did traditional agriculture with its low but dependable yields survive for 10,000 years? The answer must be that biologically fixed nitrogen and that derived from organic manures have been important components of building soil fertility since the beginning of agriculture. Several groups of bacteria are known to fix large quantities of fertilizer nitrogen in the soil. Of these microorganisms, the most important are the species of *Rhizobium* that have developed a symbiotic relationship with the roots of leguminous plants. According to Buris [2], 175 million tonnes of N_2 are biologically fixed annually of which 35 million tonnes are fixed by the Rhizobia through the process of nodulation in the roots of legumes. Some of the more efficient systems of this symbiotic nitrogen fixation are Rhizobium–soybean (100 kg/ha) and Rhizobium–lucerne (200–300 kg/ha). Some nitrogen is also fixed in the atmosphere through lightening which finds its way in the soils and in the oceans.

Just how important biological nitrogen fixation has been for human nutrition can be seen from the observation that the estimated half of the 23 million tonnes of nitrogen consumed as human food comes from biological nitrogen fixed by bacteria [5].

Soybean a Model of Physiological Efficiency

Scientists have been fascinated with the fact that plants like soybean, a short duration crop, can give a seed yield of 2.5 tonnes per hectare with more than 40% protein and more than 16% edible oil without any application of fertilizer nitrogen. Soybean genome has already been sequenced with a predicted number of nearly 46,000 genes. Following an understanding of the function of many of these genes, some of the biochemical pathways involved in the physiology of this wonder crop may become available for genetic transformation studies.

The ultimate objective of current research in biological nitrogen fixation is to transfer the NIF genes into crops plants like wheat and rice so that they can fix their own nitrogen like the legumes and do not remain dependent on industrially produced fertilizers with their high costs. Clearly, as the twenty-first century advances, we may come to have a different kind of agriculture deriving much greater support from renewable resources of energy.

Modern Biotechnology

The high-yielding varieties of wheat and rice made a major contribution to increased food production at a time when it was needed most. The problem of food security for many developing countries, however, has not gone away. Human populations in these countries continue to increase, and once again, some of them, especially those of sub-Saharan Africa and South Asia remain under pressure to achieve higher growth rates in the production of food grains. Another scientific advance would be needed to develop a new generation of high-yielding varieties resistant to diseases and pests and with an in-built capacity to perform well under conditions of abiotic stresses resulting from climate change.

Modern biotechnology, a product of advances in molecular biology, in the past 50 years, started to receive attention in this context with its promise of making crop improvement even more effective. Some of the advances which appeared particularly relevant in this regard included functional genomics for identifying genes of economic interest in food crops, development of transgenic crop varieties [8] and marker assisted selection to accelerate the process of plant breeding. A major international effort involving collaborative research between scientists from institutions in the developed and developing countries would be needed to identify new genes, alleles and quantitative trait loci (QTLs). The QTLs are particularly important for they may provide the needed genetic variation for higher grain yields and for tolerance to drought, insect pests and pathogenes. Marker assisted selection should help to cut down the time required for transferring such QTLs into the genetic background of the existing high-yielding varieties. Also, with the availability of new genes or QTLs for durable disease resistance some of the old varieties of wheat and rice which had to be phased out, as they became susceptible to disease, could be revived.

Some of the promise of modern biotechnology is already being achieved. Genes for insect pests and disease resistance have been transferred from bacteria into crop plants like cotton, soybean and rapeseed-mustard. These genetically transformed varieties already cover millions of hectares of crop land. The scientists are now working for the development of a second generation of genetically transformed varieties for quantitative traits like higher grain yields and improved nutritional quality. The focus in the twentieth century has been on calorie mal-nutrition and development of high-yielding varieties. In the twenty-first century higher starch yield of food grains will come with protective nutrients like iron and zinc. Already, rice has been genetically transformed for the beta-carotene synthesis pathway. Similar transformation will be needed for folic acid, vitamin B-12 and other mineral and vitamin nutrients.

Modern biotechnology in the twenty-first century will also be making a major impact on the lives of millions of small and marginal farmers. These farmers, living on degraded lands of low soil fertility and limited moisture, practice farming systems in which crop and animal production are totally integrated. Their first and foremost need is to improve the nutrition of their cattle which subsist mostly on crop residues. Recombinant DNA technology would be helping to evolve new strains of micro-organisms for more efficient bio-conversion of these crop residues in order to improve their digestibility and nutritive value. Also, many more strains of bacteria and fungi would be genetically transformed for fixing nitrogen and for solubilising phosphorus in the lands of these farmers.

In conclusion, agriculture of the twenty-first century will see a different kind of focus both in research and development. While increased production of food grains and other commodities will continue to be important in view of the unrelenting population pressures in many developing countries, the sustainability and safeguard of environment and natural resources will receive much greater attention. Farmers in the second half of the twenty-first century will be combining high-crop yields with management practices based on renewable resources of energy, and the scientists will be moving away from a single minded pursuit of genetic improvement to greater focus on development of new resource conservation and precision farming practices.

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