CHAPTER 1

Plant Breeding Goals and Strategies for the 1980s

N. E. Borlaug

I have spent nearly 40 years in food-deficit nations trying to apply conventional techniques of genetics and plant breeding along with all the other techniques that go with crop genetic improvement. These include cultural practice, restoration of soil fertility, and protection of crops against diseases, insects, and weeds. But these technological developments must be linked to economic policies. The best technology in the world will do nothing to change food production until someone goes the extra mile—until these developments are linked to people who determine budget allocations for research and development and for production. These are the people who frequently sit in the Ministries of Finance or Planning, and it's a curious world for the biologists who are trying to get the technology they have developed into a position where it can exert its influence. Those who have been privileged to work in academia all their lives should never make the mistake of thinking that the best technology will move quickly into commercial production. It will not, particularly if economic policies prohibit this. This is particularly true in regard to small farmers who live close to starvation. For them, the level of acceptable risk is much smaller than it is for farmers in the United States.

Having said that, let me briefly express my own points of view as they relate to the wonderful new developments of biotechnology. It is important to set the stage about the magnitude of the problem we will face in the next 40 to 60 years. Let's quickly look back before we look ahead. Agriculture is a recent invention—only 12,000 years old. Remember that before agriculture it was impossible to build cities of any size. The human race was nomadic, following drifting herds as hunters and supplementing a meat diet with wild plants, roots, nuts, grains, and fruit. It's hard to believe that all of our knowledge of agriculture, breeding, genetics and the new knowledge of biotechnology have come about in such a short period of time. Also remember, it took us from that beginning 12,000 years ago until 1975 to produce 3.3 billion metric tons of all types of food products (uncorrected for moisture). This figure comprises a vast number of different products that go into the diets of people in different parts of the world. In 1975, 98% of food production came from the land and only 2% from the ocean and inland waters, and world population was 4 billion people.

The problem ahead is this: at the 1975 growth rate, the population would double in 40 years, by the year 2015. Population growth has begun to slow (considerably in some countries), and it's essentially static or approaching zero in a number of countries. However, growth is still explosive in others, such as in Africa, and it's likely to go on that way for some period of time. So it is almost certain that the population will double from 4 to 8 billion in 50 to 60 years. In addition, other kinds of disasters are possible, such as drought, plant disease, and increased loss of soil fertility. Hence, in the short period of 50 or 60 years, we are going to have to increase food production by as much as we were able to achieve over the 12,000 years up to 1975. Furthermore, up until only about 70 or 80 years ago, most of the increase in food production came from expanding the cultivated area. Only recently have we seen an increase in yield of crops grown on the area already under cultivation. Biotechnology is aimed at developing cultivars that have the ability and genetic potential to reach an even higher level of productivity when properly sown and planted.

How have these changes taken place in the agriculture of the United States? They didn't happen overnight. The groundwork for this progress was laid back in 1862 when several bills became law in a period of about 6 weeks. Perhaps the most important was the Morrill Act, which provided states with federal lands for the establishment of the land-grant colleges and universities. These institutions originally specialized in practical fields such as agriculture, but they've grown into some of the largest universities with faculties in everything from law to medicine. At the same time, the U.S. Department of Agriculture was established. At first a small bureau, it has grown and has coordinated agricultural development in the United States. Finally, the Homestead Act gave land to people, especially new immigrants. It had a tremendous impact and was responsible for much of the migration into the open spaces to the west. People, who didn't know how to restore fertility to the worn-out lands of New England abandoned those lands and moved west with the Homestead Act. I have one very personal bit of evidence of that. In a small cemetery near the little farming community where I grew up in northeast Iowa the tombstones give evidence that nearly all of the people buried there were born in Vermont and New Hampshire. They were a part of that migration. Now what did that have to do with the development of agriculture? This activity put the people onto new, rich farmland, and resulted in at least four generations of increased agricultural production. Later on, with increased industrialization and increased demand for different kinds of goods, new industries, small and large, began to absorb people off the land into higher paying jobs in industry, commerce, and the professions. Today only about 2.1% of the total U.S. population that is economically active lives on and works the land, but there's still a great productivity in the United States, not only for domestic consumption, but also for export, which over the last several years has accounted for $40 billion of agriculture produce. In the process, the size of individual farms has increased in the 40 years since I left the farm and went to the university. The average size of the American farm at that time was about 160 acres. Today it's about 430 acres. However, just the opposite situation exists in most of the other densely populated countries of the world. With each new generation more and more fragmentation occurs, and 50–60% or more of the population still lives on the land in misery and poverty. The agriculture of countries with low productivity is very difficult to change.

Let's look at the other aspects that contributed to this pattern of productivity. Apparently, when Congress passed the three acts in 1862, they thought everything would unfold according to plan, and the sons and daughters of the land for whom these institutions were established would suddenly become more productive. However, it didn't work that way, and 25 years later Congress passed the Hatch Act. There had been growing concern that professors of agriculture were too theoretical. For example, many didn't even know how to plow. The topics they were teaching the sons and daughters of farmers had no relevance. The Hatch Act provided federal funds for the establishment of state agricultural experimental stations which were affiliated with the universities. Much later, in 1914, the Extension Act was put into operation. This fostered the flow of information from the universities and experimental stations back to the farms. Along with the Morrill and Hatch acts, this was the third leg of the stool that became the triumvirate that led to the change and productivity. Remember, from 1862 to 1914, there was not a very great change in agricultural yields. There was some, largely because the farm size could grow as machinery and mechanization improved. Consequently, as long as there was a market, each farm could buy and sell more of the goods that were needed to increase their standard of living. But there were no major breakthroughs; that shows how long the gestation period was.

In all probability, the first major breakthrough on the genetic front was hybrid corn. Had it not been for the economic collapse of the 1920s and the early 1930s it would have come 10 to 15 years earlier. The Pioneer Hybrid Seed Company was established in 1926, but before it could successfully market its hybrids, the Great Depression began. I saw corn being burned for fuel because it was cheaper than coal in the early 1930s in the Midwest. There was no market for hybrid corn until World War II. Then, when the markets opened up, hybrid technology which had resembled pieces of a jigsaw puzzle from the late 1800s up to 1940 suddenly came together in the right mesh, and crop production increased dramatically. For the 17 most important crops (food, feed, tuber, and fiber) that were grown at that time on more than a million acres, the total production in 1940 was 252 million metric tons. But by 1980, it had increased to 610 million tons, and that had been achieved with an increase of only 3% in the cultivated land area. With 1940 technology, this would have required cultivation of an additional area equivalent to all the land east of the Mississippi River excluding that of Illinois, Wisconsin, and Michigan. Alternatively, 70% of all pasture and grazing lands could have been plowed up, and 65% of the forest lands chopped down. Even then, more land would have been needed, because that forest and grazing land would have been of poorer quality. Hence, the increased productivity was achieved because of technological innovation between 1940 and 1980. But it was a slow proposition.

The question now is, will it be two decades, or four or five decades before many of today's new technologies are put into production? I think that it behooves all of us to try to find ways to cut this period as much as we can. Remember that in 50 or 60 years we are going to have to double what we achieved largely through expanded area in 12,000 years.

Let me mention briefly some of my own experiences that I think bear indirectly on the slow progress of translating technology to production. This is especially true in developing nations where there has always been a shortage of trained people across all the disciplines that bear on food and fiber production. It's not a matter of 5 years or 10 years. At best it's 25 years and it may well be closer to 35–40 years in countries where a large proportion of the population lives on the land. I think we know how to train people pretty well by now. But it is a different matter to keep those organizations once formed and to employ those people once trained. It is necessary to talk to the people who sit on the planning commissions—as we say in Spanish, "Esos que cortan el queso y repartan el caso," those who sit up there and carve the cheese and decide its distribution. Communicating with bureaucrats is a continuing job. If this job is neglected, the research organizations will become sterile again.

When I first began to work in Mexico in the Rockefeller Foundation Program, I was assigned to work on wheat, and I'd never worked on wheat in my life. I grew up with corn and other crops, but that's the way it was. I began to see that Mexico needed major efforts in two areas. The first was the Senora Desert in the Pacific Northwest, an irrigated area on the coastal plain. A second effort was needed in the old colonial parts of Central Mexico, the Bajio. In Northwest Mexico I saw that in 3 years from 1939 to 1941, they had lost the vast majority of their crops to wheat stem rust. I recalled what I had been taught in graduate school about how to organize breeding programs, one generation a year. It would have required at least 11 years to produce a rust-resistant variety.

I said, "Look, my luck will never last that long. And when the next rust epidemic comes, I'll be thrown out of the country as someone who failed and I'll probably be run out of the Rockefeller Foundation at the same time." But we developed a program for Mexico that turned out to have implications far beyond the Mexican borders.

I mention this because I think some of these issues need to be looked at from the point of view of getting them on stage fast. I went into the Sonora and planted our segregating populations as the farmers plant, on the first of November. At this time the days were getting shorter. This land was at 28 degrees north latitude and about 30 meters above sea level. Stem rust was one of the main problems in this irrigated area. We harvested in April and looked for an area where we could plant a second generation in summer, i.e., where the temperatures were favorable. The only places I could find that were close to Mexico City were the valleys of Mexico and Toluca, one being 2200 meters in elevation, the other 2600 meters, both at 18 degrees north latitude. When we planted the wheat, the days were getting longer. By selecting under those two very diverse conditions with different groups of pathogens exerting their pressures, we were trying to help our germplasm build up tolerance to those pathogens. Suddenly, nothing the book said applied. We had some varieties that were equally good in the high country and the coastal plains. In a short period of time I selected lines with increased yields. In the process we controlled the diseases. I also had to battle with the economists. At that time there were very few economists in the government of Mexico, and it was pretty easy to get the ear of a political leader. It's more difficult now because there are more layers, and the economic advisors have much more power. As I learned how to move around in the jungles of bureaucracy and to get the ear of those who made economic decisions, everything started to unfold.

We did other things. When you start to fertilize, wheat plants grow tall and fall down. We looked for dwarfing genes in many parts of the world, including all over Mexico, but none of them performed well in the field. We didn't have decent microscopes at the time, but I suspect that many of the dwarfs were aneuploids. Finally, we did acquire some of the Japanese and Oriental dwarfing genes. These genes were completely susceptible to local pathogens, but we went to work on them as we had with the earlier Mexican varieties. We used back and forth shuttle breeding, and soon we had dwarf varieties that had an entirely different level of productivity when properly managed.

To make this story short, I saw Mexican wheat production go from 350,000 tons in the 1940s when I arrived to 4.4 million in 1984. The yields have increased dramatically. More important than the increase in productivity was what happened elsewhere. Young people came to train with us in practical crop improvement. The program at the International Maize and Wheat Improvement Center (CIMMYT) was focused on practical breeding and field work. I made a survey in 1960 when the Rockefeller Program was finishing its tour of duty in Mexico.

The foundation had trained the people and was turning the program over to the young Mexican scientists it had trained. The Food and Agriculture Organization asked me to look at the wheat programs from Morocco to India and give them some suggestions. This review was done jointly with the Rockefeller Foundation. In at least two countries, I saw a lot of well-trained scientists who were seldom in the field. On the contrary, they were nicely dressed in white coats, and they worked in their labs and in office buildings. They had no impact whatsoever on agricultural production. It was necessary to get them out of the labs and teach them that there had to be some linkage between the theory they learned in the universities and its applications in the field. The application of ideas in agriculture requires some physical sweat. Sweat is not necessarily degrading, even if it's done by an educated person or a scientist. There seems to be a kind of mental block against hard work. It used to be that highly educated people weren't supposed to work with their hands, and that has become one of our main problems. So at CIMMYT we began bringing in young people from many countries who worked with us for a year in the application of science and technology in their own disciplines.

Furthermore, when they went back to their home countries, they took back samples of seed. After a while we started to get data from them. They reported that some of the Mexican varieties were well suited to their homelands. Of course, what was done was to select out from these populations new varieties that could tolerate changes in temperature within the limits that we were able to work under and that had tolerance against a whole range of pathogenic organisms. These varieties had high levels of genetic yield potential built in which was expressed when they were properly managed.

What were the implications? In India, when these new varieties were introduced between 1962 and 1966, the average production of wheat was 11 million metric tons. Last year it was 41.5 million metric tons. That increase in productivity provided 65% of the calories for 223 million more people just with that one crop alone. This production increase also introduced a whole series of other changes. As soon as they learned how to fertilize wheat, they would say "Well, in the past we could only grow one crop a year on this land, even if it was irrigated, because of lack of soil fertility." So with fertilization, they began to double-crop rice, wheat, and even potatoes. In some cases, they even triple-cropped. After this a whole series of events occurred. Very soon high-yielding rice varieties were developed. India became self-sufficient in food grain production for the first time in 1978 and was able to stockpile about 22 million tons of grain in 1978 and early 1979. In 1979 India had the worst monsoon in 70 years, but we didn't hear about starvation. They lived off their reserves, and now they're back on track again. I mention this simply to show that it was about 23 years from the time we started the program in Mexico until it began to have an impact on India, Pakistan, and a number of other countries. We can't wait that long to accomplish the job that we've got ahead of us.

It occurs to me that we have to use biotechnology more successfully than we have used conventional breeding in the past. In the development of basic technology of genetics and cytology of wheat, work could just as easily have been done in commercial varieties as in purely experimental lines. Instead, genetics and cytology of wheat was done on the Chinese Spring variety, one that has been commercially useless. Thus all the knowledge of genetics and aneuploidy and the whole gamut of cytogenetics, achieved by wonderfully competent scientists, was accumulated in this variety. Nobody has ever been able to use Chinese Spring or correct its deficiencies to produce something of commercial worth. This represents the sum of 50–60 years of work. Had these accomplishments been the result of work on a different variety, practical results would have been obtained much more quickly. For that reason, I believe those who are working in biotechnology should start out with the best varieties that are available. Complications may well arise, but, in the long run, decades of time may be saved. Start with a variety that carries a good combination of genes, not only for yield productivity, but for breadth of adaptation and for disease resistance. This is important: variety development is a constantly changing picture because of the way pathogens mutate and change.

There are two or three other points that need to be made. The tremendous yield improvements in wheat were achieved in the bread wheat, *Triticum aestivum*. Bread wheat is made up of three genomes (A, B, and D) of seven chromosomes each, coming from three wild parents that came together way back in prehistory. Bread wheat is unique in that the D genome contains the genes for dough elasticity, which permits the process of fermentation that results in the big expansion in the loaf. Recently, we started working on *Triticum durum* (A and B genome) in a concentrated way. The durums are used for producing spaghetti and crackers. Probably less than 2% of all research done in plant breeding and in genetics and cytogenetics on wheat had been done on *T. durum*. However, after concentrated effort in the last 10 years, durum outyields bread wheat by 700 kilos to a ton per hectare in the areas where we developed the best-yielding Mexican wheats. Now we've got the problem of how to get the genes for elasticity into the AB genome. The durum wheat has tough dough that doesn't make a good loaf of bread. New cell culture and genetic engineering tools may accomplish this goal.

A second opportunity for crop improvement is with *Triticale* (a hybrid between wheat, *Triticum*, and rye, *Secale*). We started working on triticale in cooperation with the University of Manitoba in 1965. The best triticales from that program yielded about 40% of the best wheats in Northwest Mexico. That's no longer the case. Those triticales were tall, and day-length sensitive. They needed a long day, and under our short Canadian days they were very late, poor yielding, and highly sterile. In addition, the grain that was set was shriveled and wasn't fit for chicken feed. All sorts of problems were encountered. We planted about 2 hectares of F_1 plants that seemed to perform quite poorly. However, in this big field of segregating plants, Mother Nature took a hand and made a cross. Two generations later, after selecting and evaluating a lot of plants, we found seven homozygous plants that were uniform for complete fertility. In addition, genes for dwarfing and earliness that were not present in the original triticales were expressed in these triticales. Obviously, a cross had occurred between triticale and one of the Mexican wheats that was growing nearby. At that time we didn't know what was responsible for the restored fertility. Later, we found that a chromosome substitution had occurred of wheat back into the rye genome. Curiously, when we crossed the new fertile triticale to many other triticales, the fertility was transmitted. We have since reconstituted the rye genome into these plants and now have complete fertility in triticale. Some lines have all the rye chromosomes present, while others have various kinds of chromosome substitutions. Fertility has been moved all around through the program and is no longer a problem in triticales.

We are still working on trying to improve the grain in these triticales. Those we work with are a cross between the durum wheats—*Triticum durum* (AABB), a tetraploid—and rye. Dr. Arne Muntzing, one of the pioneers in Europe at the University of Lund, spent his lifetime working on hexaploid triticales. These are bread wheat (AABBDD) crossed with rye (RR). Sanchez Monae, from the University of Madrid, first combined the tetraploid durums and ryes into the background that we worked with at the University of Manitoba. The original bread wheat × rye triticales never had a reasonable yield. We've now found that the best triticales are combinations of *Triticum durum* and the ryes. However, these lines don't have elasticity. We could approach this problem in either of two ways: (1) Transfer elasticity from the D genome in bread wheat over into the AB genome of durum wheat and use these durums to make our hybrids. (2) Select for triticales that have elasticity. We are sure we can do this with time; it'll probably be 15 or 20 years using conventional breeding.

I would like to live long enough to see triticale become an important crop in the world. It is becoming important in local areas in a few places. It grows better than wheat on problem soils. Some of our friends in the south of Brazil where the soil is very acid grow triticale because it tolerates acidity better than wheat. The same is true in Poland. In this respect triticale resembles the rye parent. Similarly, in the red soils of the hills of Michoacan in Mexico triticale is becoming a commercial crop. At this time the problem is largely one of marketing, for this is a new product. No one has ever seen a cereal like this. With triticale we've got a sales job on our hands, but I think we can make it work.

I'd like to discuss one final example where biotechnology can help conventional breeding. Many of you know about the value of the opaque-2 gene in maize. When it was first discovered, it was not thought to have any economic or physiological importance. But in 1964 a young graduate student at Purdue University, Lynn Bates, surveyed a number of corn varieties, and he discovered that opaque-2 had twice the level of tryptophan and nearly twice the level of lysine, compared to those of standard varieties. From a nutritional standpoint for humans and monogastric animals, tryptophan and lysine are the two essential amino acids found in inadequate amounts in cereals.

Everybody became enthusiastic. These findings were tested first on rats, then swine, and then children. These amino acids, when available, have a tremendous impact on physiological development. However, associated with opaque-2 was fluffy starch in the endosperm. Even if opaque lines could be obtained that had the same ear size and kernel size as the best hybrids, yield would still be off 20–25% because of the fluffiness of the starch and the low density of the kernels. Worse yet, because of their soft texture the opaque-2 lines were highly susceptible to insect damage, both in the field and in the warehouse.

The result was that everybody quit working on it except our CIMMYT group program under Dr. Ernest W. Sprague. At CIMMYT, because of the unique, close relationship between our protein quality laboratory, headed by Dr. Evangelina Villegas and Dr. Surinder K. Vasil, and the breeding programs, they noticed that some populations contained kernels that had islands of hard, corny starch. Microsampling showed that these islands had the same lysine and tryptophan content as the soft starch. Hence, they selected for hard starch without destroying the embryos. The best selections were transplanted to paper pots in the greenhouse and then to the fields where they were crossed. This has been repeated now for 14 cycles, and a very broadly adapted variety Tuchspania 1 has been developed. This variety has essentially the same lysine and tryptophan of the original opaque-2 in a kernel type that is indistinguishable from the dent parent or from the flint parent from which it was developed. I have been trying to be a salesman for some of these varieties and get them into production in several Central American countries and in Mexico. It so happens that this variety is broadly adapted to lowlands. It is adapted for the coasts of Central America, and for the two southern provinces of China, and for several countries of West Africa. In addition, there are other breeding lines in the program that will fit other elevations.

Other genes that control lysine should also be considered, as we will probably need still another dose at some stage in the future. For example, if opaque-2 is fed to pigs, it is necessary to supplement the diet with soybean meal from time of weaning until the pig weighs about 30 kg to get proper growth. The pigs can then be fattened at a good rate with just the lysine, tryptophan, and the minerals, chemicals, and vitamins contained in opaque-2. However, since there are other genes available in *Zea* that could be inserted into cultivated corn using cell culture techniques or genetic engineering, this new technology permits us to make another step in that direction.

In the time it has taken to read this chapter, there must now be about 6000 more people to feed. It is clear that cell culture technology must be put into operation a lot faster than we've done with conventional breeding in the past.