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# History and role of plant breeding in society

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## Purpose and expected outcomes

*Agriculture is the deliberate planting and harvesting of plants and herding animals. This human invention has, and continues to, impact on society and the environment. Plant breeding is a branch of agriculture that focuses on manipulating plant heredity to develop new and improved plant types for use by society. People in society are aware and appreciative of the enormous diversity in plants and plant products. They have preferences for certain varieties of flowers and food crops. They are aware that whereas some of this variation is natural, humans with special expertise (plant breeders) create some of it. Generally, also, there is a perception that such creations derive from crossing different plants. The tools and methods used by plant breeders have been developed and advanced through the years. There are milestones in plant breeding technology as well as accomplishments by plant breeders over the years. This introductory chapter is devoted to presenting a brief overview of plant breeding, including a brief history of its development, how it is done, and its benefits to society. After completing this chapter, the student should have a general understanding of:*

- 1 The historical perspectives of plant breeding.
- 2 The need and importance of plant breeding to society.
- 3 The goals of plant breeding.
- 4 Trends in plant breeding as an industry.
- 5 Milestones in plant breeding.
- 6 The accomplishments of plant breeders.
- 7 The future of plant breeding in society.

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## What is plant breeding?

Plant breeding is a deliberate effort by humans to nudge nature, with respect to the heredity of plants, to an advantage. The changes made in plants are permanent and heritable. The professionals who conduct this task are called **plant breeders**. This effort at adjusting the *status quo* is instigated by a desire of humans to improve certain aspects of plants to perform new roles or enhance existing ones. Consequently, the term “plant breeding” is often used synonymously with “plant improvement” in modern society. It needs to be emphasized that the

goals of plant breeding are focused and purposeful. Even though the phrase “to breed plants” often connotes the involvement of the sexual process in effecting a desired change, modern plant breeding also includes the manipulation of asexually reproducing plants (plants that do not reproduce through the sexual process). Breeding is hence about manipulating plant attributes, structure, and composition, to make them more useful to humans. It should be mentioned at the onset that it is not every plant character or trait that is amenable to manipulation by breeders. However, as technology advances, plant breeders are increasingly able to

accomplish astonishing plant manipulations, needless to say not without controversy, as is the case involving the development and application of **biotechnology** to plant genetic manipulation. One of the most controversial of these modern technologies is **transgenesis**, the technology by which gene transfer is made across natural biological barriers.

Plant breeders specialize in breeding different groups of plants. Some focus on field crops (e.g., soybean, cotton), horticultural crops (e.g., vegetables), ornamentals, fruit trees (e.g., citrus, apple), forage crops (e.g., alfalfa, grasses), or turf species. More importantly, breeders tend to focus on specific species in these groups. This way, they develop the expertise that enables them to be most effective in improving the species of their choice. The principles and concepts discussed in this book are generally applicable to breeding all species. However, most of the examples supplied are from breeding field crops.

### Goals of plant breeding

The plant breeder uses various technologies and methodologies to achieve targeted and directional changes in the nature of plants. As science and technology advance, new tools are developed while old ones are refined for use by breeders. Before initiating a breeding project, clear breeding objectives are defined based on factors such as producer needs, consumer preferences and needs, and environmental impact. Breeders aim to make the crop producer's job easier and more effective in various ways. They may modify plant structure so it can resist lodging and thereby facilitate mechanical harvesting. They may develop plants that resist pests so the farmer does not have to apply pesticides or can apply smaller amounts of these chemicals. Not applying pesticides in crop production means less environmental pollution from agricultural sources. Breeders may also develop high-yielding varieties (or **cultivars**) so the farmer can produce more for the market to meet consumer demands while improving his or her income. The term cultivar is reserved for variants deliberately created by plant breeders and will be introduced more formally later in the book. It will be the term of choice in this book.

When breeders think of consumers, they may, for example, develop foods with higher nutritional value and that are more flavorful. Higher nutritional value means reduced illnesses in society (e.g., nutritionally related ones such as blindness or ricketsia) caused by the

consumption of nutrient-deficient foods, as obtains in many developing regions where staple foods (e.g., rice, cassava) often lack certain essential amino acids or nutrients. Plant breeders may also target traits of industrial value. For example, fiber characteristics (e.g., strength) of fiber crops such as cotton can be improved, while oil crops can be improved to yield high amounts of specific fatty acids (e.g., the high oleic content of sunflower seed). The latest advances in technology, specifically genetic engineering technologies, are being applied to enable plants to be used as bioreactors to produce certain pharmaceuticals (called **biopharming** or simply **pharming**).

The technological capabilities and needs of societies of old, restricted plant breeders to achieving modest objectives (e.g., product appeal, adaptation to production environment). It should be pointed out that these "older" breeding objectives are still important today. However, with the availability of sophisticated tools, plant breeders are now able to accomplish these genetic alterations in novel ways that are sometimes the only option, or are more precise and more effective. Furthermore, as previously indicated, they are able to undertake more dramatic alterations that were impossible to attain in the past (e.g., transferring a desirable gene from a bacterium to a plant!). Some of the reasons why plant breeding is important to society are summarized next.

### Concept of genetic manipulation of plant attributes

The work of Gregor Mendel and the further advances in science that followed his discoveries established that plant characteristics are controlled by hereditary factors or **genes** that consist of DNA (deoxyribose nucleic acid, the hereditary material). These genes are expressed in an environment to produce a trait. It follows then that in order to change a trait or its expression, one may change the *nature* or its genotype, and/or modify the *nurture* (environment in which it is expressed). Changing the environment essentially entails modifying the growing or production conditions. This may be achieved through an agronomic approach, for example, the application of production inputs (e.g., fertilizers, irrigation). Whereas this approach is effective in enhancing certain traits, the fact remains that once these supplemental environmental factors are removed, the expression of the plant trait reverts to the *status quo*. On the other hand, plant breeders seek to modify plants with respect

to the expression of certain attributes by modifying the genotype (in a desired way by targeting specific genes). Such an approach produces an alteration that is permanent (i.e., transferable from one generation to the next).

### Why breed plants?

The reasons for manipulating plant attributes or performance change according to the needs of society. Plants provide food, feed, fiber, pharmaceuticals, and shelter for humans. Furthermore, plants are used for aesthetic and other functional purposes in the landscape and indoors.

#### Addressing world food, feed, and nutritional needs

Food is the most basic of human needs. Plants are the primary producers in the **ecosystem** (a community of living organisms including all the non-living factors in the environment). Without them, life on earth for higher organisms would be impossible. Most of the crops that feed the world are cereals (Table 1.1). Plant breeding is needed to enhance the value of food crops, by improving their yield and the nutritional quality of their products, for healthy living of humans. Certain plant foods are deficient in certain essential nutrients to the extent that where these foods constitute the bulk of a staple diet, diseases associated with nutritional deficiency are often common. Cereals tend to be low in lysine and threonine, while legumes tend to be low in cysteine and methionine (both sulfur-containing amino acids). Breeding is needed to augment the nutritional quality of food crops. Rice, a major world food, lacks

**Table 1.1** The 25 major food crops of the world, ranked according to total tonnage produced annually.

1	Wheat	11	Sorghum	21	Apple
2	Rice	12	Sugarcane	22	Yam
3	Corn	13	Millet	23	Peanut
4	Potato	14	Banana	24	Watermelon
5	Barley	15	Tomato	25	Cabbage
6	Sweet potato	16	Sugar beet		
7	Cassava	17	Rye		
8	Grape	18	Orange		
9	Soybean	19	Coconut		
10	Oat	20	Cottonseed oil		

Source: J.R. Harlan. 1976. Plants and animals that nourish man. *In*: Food and agriculture, A Scientific American Book. W.H. Freeman and Company, San Francisco.

pro-vitamin A (the precursor of vitamin A). The “Golden Rice” project, currently underway at the International Rice Research Institute (IRRI) in the Philippines and other parts of the world, is geared towards developing, for the first time ever, a rice cultivar with the capacity to produce pro-vitamin A. An estimated 800 million people in the world, including 200 million children, suffer chronic undernutrition, with its attendant health issues. Malnutrition is especially prevalent in developing countries.

Breeding is also needed to make some plant products more digestible and safer to eat by reducing their toxic components and improving their texture and other qualities. A high lignin content of the plant material reduces its value for animal feed. Toxic substances occur in major food crops, such as alkaloids in yam, cynogenic glucosides in cassava, trypsin inhibitors in pulses, and steroidal alkaloids in potatoes. Forage breeders are interested, among other things, in improving feed quality (high digestibility, high nutritional profile) for livestock.

#### Addressing food needs for a growing world population

In spite of a doubling of the world population in the last three decades, agricultural production rose at an adequate rate to meet world food needs. However, an additional 3 billion people will be added to the world population in the next three decades, requiring an expansion in world food supplies to meet the projected needs. As the world population increases, there would be a need for an agricultural production system that is apace with population growth. Unfortunately, arable land is in short supply, stemming from new lands that have been brought into cultivation in the past, or surrendered to urban development. Consequently, more food will have to be produced on less land. This calls for improved and high-yielding varieties to be developed by plant breeders. With the aid of plant breeding, the yields of major crops have dramatically changed over the years. Another major concern is the fact that most of the population growth will occur in developing countries where food needs are currently most serious, and where resources for feeding people are already most severely strained, because of natural or human-made disasters, or ineffective political systems.

#### The need to adapt plants to environmental stresses

The phenomenon of global climatic change that is occurring over the years is partly responsible for

modifying the crop production environment (e.g., some regions of the world are getting drier and others saltier). This means that new cultivars of crops need to be bred for new production environments. Whereas developed economies may be able to counter the effects of unseasonable weather by supplementing the production environment (e.g., by irrigating crops), poor countries are easily devastated by even brief episodes of adverse weather conditions. For example, the development and use of drought-resistant cultivars is beneficial to crop production in areas of marginal or erratic rainfall regimes. Breeders also need to develop new plant types that can resist various biotic (diseases, insect pests) and other abiotic (e.g., salt, drought, heat, cold) stresses in the production environment. Crop distribution can be expanded by adapting crops to new production environments (e.g., adapting tropical plants to temperate regions). The development of photoperiod-insensitive crop cultivars would allow the expansion in production of previously photoperiod-sensitive species.

### **The need to adapt crops to specific production systems**

Breeders need to produce plant cultivars for different production systems to facilitate crop production and optimize crop productivity. For example, crop cultivars must be developed for rain-fed or irrigated production, and for mechanized or non-mechanized production. In the case of rice, separate sets of cultivars are needed for upland production and for paddy production. In organic production systems where pesticide use is highly restricted, producers need insect- and disease-resistant cultivars in crop production.

### **Developing new horticultural plant varieties**

The ornamental horticultural production industry thrives on the development of new varieties through plant breeding. Aesthetics is of major importance to horticulture. Periodically, ornamental plant breeders release new varieties that exhibit new colors and other morphological features (e.g., height, size, shape). Also, breeders develop new varieties of vegetables and fruits with superior yield, nutritional qualities, adaptation, and general appeal.

### **Satisfying industrial and other end-use requirements**

Processed foods are a major item in the world food supply system. Quality requirements for fresh produce

meant for the table are different from those used in the food processing industry. For example, there are table grapes and grapes bred for wine production. One of the reasons why the first **genetically modified (GM)** crop (produced by using genetic engineering tools to incorporate foreign DNA) approved for food, the FlavrSavr® tomato, did not succeed was because the product was marketed as a table or fresh tomato, when in fact the gene of interest was placed in a genetic background for developing a processing tomato variety. Other factors contributed to the demise of this historic product. Different markets have different needs that plant breeders can address in their undertakings. For example, the potato is a versatile crop used for food and industrial products. Different varieties are bred for baking, cooking, fries (frozen), chipping, and starch. These cultivars differ in size, specific gravity, and sugar content, among other properties. A high sugar content is undesirable for frying or chipping because the sugar caramelizes under high heat to produce undesirable browning of fries and chips.

## **Plant breeding through the ages**

Plant breeding as a conscious human effort has ancient origins.

### **Origins of agriculture and plant breeding**

In its primitive form, plant breeding started after the invention of agriculture, when people of primitive cultures switched from a lifestyle of hunter-gatherers to sedentary producers of selected plants and animals. Views of agricultural origins range from the mythological to ecological. This lifestyle change did not occur overnight but was a gradual process during which plants were transformed from being independent, wild progenitors, to fully dependent (on humans) and domesticated varieties. Agriculture is generally viewed as an invention and discovery. During this period, humans also discovered the time-honored and most basic plant breeding technique – **selection**, the art of discriminating among biological variation in a population to identify and pick desirable variants. Selection implies the existence of variability. In the beginnings of plant breeding, the variabilities exploited were the naturally occurring variants and wild relatives of crop species. Furthermore, selection was based solely on the intuition, skill, and judgment of the operator. Needless to say, this form of selection is practiced to date by farmers

in poor economies, where they save seed from the best-looking plants or the most desirable fruit for planting the next season. These days, scientific techniques are used in addition to the aforementioned qualities to make the selection process more precise and efficient. Even though the activities described in this section are akin to some of those practiced by modern plant breeders, it is not being suggested that primitive crop producers were necessarily conscious of the fact that they were nudging nature to their advantage as modern breeders do.

### Plant breeding past (pre-Mendelian)

Whereas early plant breeders did not deliberately create new variants, modern plant breeders are able to create new variants that previously did not occur in natural populations. It is difficult to identify the true beginnings of modern plant breeding. However, certain early observations by certain individuals helped to lay the foundation for the discovery of the modern principles of plant breeding. It has been reported that archaeological records indicate that the Assyrians and Babylonians artificially pollinated date palm, at least 700 BC. R. J. Camerarius (aka Rudolph Camerer) of Germany is credited with first reporting sexual reproduction in plants in 1694. Through experimentation, he discovered that pollen from male flowers was indispensable to fertilization and seed development on female plants. His work was conducted on monoecious plants (both sexes occur on separate parts of the plant, e.g., spinach and maize). However, it was Joseph Koelreuter who conducted the first known systematic investigations into plant hybridization (crossing of genetically dissimilar parents) of a number of species, between 1760 and 1766. Similarly, in 1717, Thomas Fairchild, an Englishman, conducted an **interspecific cross** (a cross between two species) between sweet william (*Dianthus barbatus*) and *D. caryophyllis*, to obtain what became known as Fairchild's sweet william. Another account describes an observation in 1716 by an American, Cotton Mather, to the effect that ears from yellow corn grown next to blue or red corn had blue and red kernels in them. This suggested the occurrence of natural cross-pollination. Maize is one of the crops that has received extensive breeding and genetic attention in the scientific community. As early as 1846, Robert Reid of Illinois was credited with developing what became known as "Reid's Yellow Dent". The landmark work by Swedish botanist, Carolus Linnaeus (1707–1778), which culminated in the **binomial systems of classification** of plants, is

invaluable to modern plant breeding. In 1727, Louis Leveque de Vilmorin of the Vilmorin family of seed growers founded the Vilmorin Breeding Institute in France as the first institution dedicated to plant breeding and the production of new cultivars. There, another still commonly used breeding technique – **progeny test** (growing the progeny of a cross for the purpose of evaluating the genotype of the parent) – was first used to evaluate the breeding value of a single plant. Selected milestones in plant breeding are presented in Table 1.2.

### Plant breeding present (post-Mendelian)

Modern plant breeding depends on the principles of genetics, the science of heredity to which Gregor Mendel made some of its foundational contributions. Mendel's original work on the garden pea was published in 1865. It described how factors for specific traits are transmitted from parents to offspring and through subsequent generations. His work was rediscovered in 1900, with confirmation by E. von Tschermak, C. Correns, and H. de Vries. These events laid the foundation for modern genetics. Mendel's studies gave birth to the concept of genes (and the discipline of **genetics**), factors that encode traits and are transmitted through the sexual process to the offspring. Further, his work resulted in the formulation of the basic rules of heredity that are called Mendel's laws.

One of the earliest applications of genetics to plant breeding was made by the Danish botanist, Wilhelm Johannsen. In 1903, Johannsen developed the **pure-line theory** while working on the garden bean. His work confirmed an earlier observation by others that the techniques of selection could be used to produce uniform, true-breeding cultivars by selecting from the progeny of a single self-pollinated crop (through repeated selfing) to obtain highly homozygous lines (true breeding), which he later crossed. Previously, H. Nilson had demonstrated that the unit of selection was the plant. The products of the crosses (called **hybrids**) yielded plants that outperformed either parent with respect to the trait of interest (the concept of **hybrid vigor**). Hybrid vigor (or heterosis) is the foundation of modern hybrid crop production programs.

In 1919, D. F. Jones took the idea of a single cross further by proposing the double-cross concept, which involved a cross between two single crosses. This technique made the commercial production of hybrid corn seed economical. The application of genetics in crop improvement has yielded spectacular successes over the

**Table 1.2** Selected milestones in plant breeding

9000 BC	First evidence of plant domestication in the hills above the Tigris river
3000 BC	Domestication of all important food crops in the Old World completed
1000 BC	Domestication of all important food crops in the New World completed
700 BC	Assyrians and Babylonians hand pollinate date palms
1694	Camerarius of Germany first to demonstrate sex in plants and suggested crossing as a method to obtain new plant types
1716	Mather of USA observed natural crossing in maize
1719	Fairchild created first artificial hybrid (carnation × sweet william)
1727	Vilmorin Company of France introduced the pedigree method of breeding
1753	Linnaeus published <i>Species plantarum</i> . Binomial nomenclature born
1761–1766	Koelreuter of Germany demonstrated that hybrid offspring received traits from both parents and were intermediate in most traits; produced first scientific hybrid using tobacco
1847	“Reid’s Yellow Dent” maize developed
1866	Mendel published his discoveries in <i>Experiments in plant hybridization</i> , cumulating in the formulation of laws of inheritance and discovery of unit factors (genes)
1899	Hopkins described the ear-to-row selection method of breeding in maize
1900	Mendel’s laws of heredity rediscovered independently by Correns of Germany, de Vries of Holland, and von Tschermak of Austria
1903	The pure-line theory of selection developed
1904–1905	Nilsson-Ehle proposed the multiple factor explanation for inheritance of color in wheat pericarp
1908–1909	Hardy of England and Weinberg of Germany developed the law of equilibrium of populations
1908–1910	East published his work on inbreeding
1909	Shull conducted extensive research to develop inbreds to produce hybrids
1917	Jones developed first commercial hybrid maize
1926	Pioneer Hi-bred Corn Company established as first seed company
1934	Dustin discovered colchicines
1935	Vavilov published <i>The scientific basis of plant breeding</i>
1940	Harlan used the bulk breeding selection method in breeding
1944	Avery, MacLeod, and McCarty discovered DNA is hereditary material
1945	Hull proposed recurrent selection method of breeding
1950	McClintock discovered the <i>Ac-Ds</i> system of transposable elements
1953	Watson, Crick, and Wilkins proposed a model for DNA structure
1970	Borlaug received Nobel Prize for the Green Revolution Berg, Cohen, and Boyer introduced the recombinant DNA technology
1994	“FlavrSavr” tomato developed as first genetically modified food produced for the market
1995	<i>Bt</i> corn developed
1996	Roundup Ready® soybean introduced
2004	Roundup Ready® wheat developed

years, one of the most notable being the development of dwarf, environmentally responsive cultivars of wheat and rice for the subtropical regions of the world. These new plant materials transformed food production in these regions in a dramatic fashion, and in the process became dubbed the **Green Revolution**. This remarkable achievement in food production is discussed below.

Mutagenesis (the induction of mutations using mutagenic agents (mutagens) such as radiation or chemicals) became a technique for plant breeding in the 1920s when researchers discovered that exposing plants to X-rays increased the variation in plants. Mutation breeding

accelerated after World War II, when scientists included nuclear particles (e.g., alpha, protons, and gamma) as mutagens for inducing mutations in organisms. Even though very unpredictable in outcome, mutagenesis has been successfully used to develop numerous mutant varieties.

In 1944, DNA was discovered to be the genetic material. Scientists then began to understand the molecular basis of heredity. New tools (molecular tools) are being developed to facilitate plant breeding. Currently, scientists are able to circumvent the sexual process to transfer genes from one parent to another. In fact, genes

can now be transferred from virtually any organism to another. This newest tool, specifically called **genetic engineering**, has its proponents and detractors. Current successes include the development of insect resistance in crops such as maize by incorporating a gene from the bacterium *Bacillus thuringiensis*. Cultivars containing an alien gene for insect resistance from this particular organism are called *Bt* cultivars, diminutive of the scientific name of the bacterium. The products of the application of this alien gene transfer technology are generally called genetically modified (GM) or **transgenic** products. **Plant biotechnology**, the umbrella name for the host of modern plant manipulation techniques, has produced, among other things, molecular markers to facilitate the selection process in plant breeding.

### Achievements of modern plant breeders

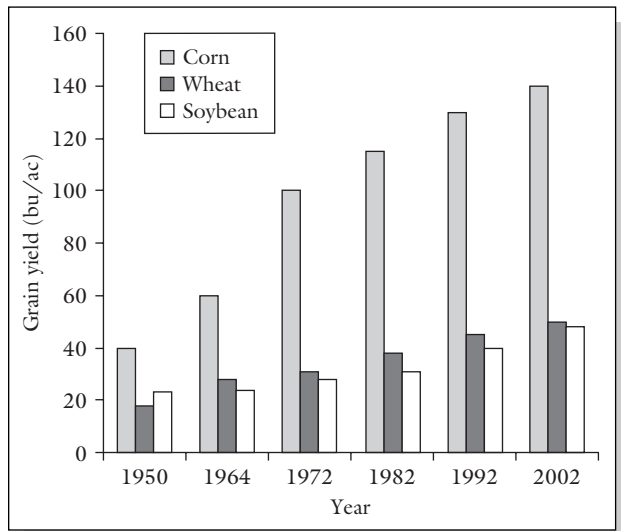
The achievements of plant breeders are numerous, but may be grouped into several major areas of impact – yield increase, enhancement of compositional traits, crop adaptation, and the impact on crop production systems.

#### Yield increase

Yield increase in crops has been accomplished in a variety of ways including targeting yield *per se* or its components, or making plants resistant to economic diseases and insect pests, and breeding for plants that are responsive to the production environment. Yields of major crops (e.g., corn, rice, sorghum, wheat, soybean) have significantly increased in the USA over the years (Figure 1.1). For example, the yield of corn rose from about 2,000 kg/ha in the 1940s to about 7,000 kg/ha in the 1990s. In England, it took only 40 years for wheat yields to rise from 2,000 to 6,000 kg/ha. These yield increases are not totally due to the genetic potential of the new crop cultivars but also due to improved agronomic practices (e.g., application of fertilizer, irrigation). Crops have been armed with disease resistance to reduce yield loss. Lodging resistance also reduces yield loss resulting from harvest losses.

#### Enhancement of compositional traits

Breeding for plant compositional traits to enhance nutritional quality or to meet an industrial need are major plant breeding goals. High protein crop varieties (e.g., high lysine or quality protein maize) have been



**Figure 1.1** The yield of major world food crops is steadily rising, as indicated by the increasing levels of crops produced in the US agricultural system. A significant portion of this rise is attributable to the use of improved crop cultivars by crop producers. bu/ac, bushels per acre. Source: Drawn with data from the USDA.

produced for use in various parts of the world. For example, different kinds of wheat are needed for different kinds of products (e.g., bread, pasta, cookies, semolina). Breeders have identified the quality traits associated with these uses and have produced cultivars with enhanced expression of these traits. Genetic engineering technology has been used to produce high oleic sunflower for industrial use, while it is also being used to enhance the nutritional value of crops (e.g., pro-vitamin A “Golden Rice”). The shelf-life of fruits (e.g., tomato) has been extended through the use of genetic engineering techniques to reduce the expression of compounds associated with fruit deterioration.

#### Crop adaptation

Crop plants are being produced in regions to which they are not native, because breeders have developed cultivars with modified physiology to cope with variations, for example, in the duration of day length (photoperiod). Photoperiod-insensitive cultivars will flower and produce seed under any day length conditions. The duration of the growing period varies from one region of the world to another. Early maturing cultivars of crop plants enable growers to produce a crop during a short window of opportunity, or even to produce two crops in

one season. Furthermore, early maturing cultivars can be used to produce a full season crop in areas where adverse conditions are prevalent towards the end of the normal growing season. Soils formed under arid conditions tend to accumulate large amounts of salts. In order to use these lands for crop production, salt-tolerant (saline and aluminum tolerance) crop cultivars have been developed for certain species. In crops such as barley and tomato, there are commercial cultivars in use, with drought, cold, and frost tolerance.

### The Green Revolution

Producing enough food to feed the world's ever increasing population has been a lingering concern of modern societies. Perhaps the most notable essay on food and population dynamics was written by Thomas Malthus in 1798. In this essay, "Essay on the principles of population", he identified the geometric role of natural population increase in outrunning subsistence food supplies. He observed that unchecked by environmental or social constraints it appears that human populations double every 25 years, regardless of the initial population size. Because population increase, according to this observation, was geometric, whereas food supply at best was arithmetic, there was implicit in this theory pessimism about the possibility of feeding ever growing populations. Fortunately, mitigating factors such as technological advances, advances in agricultural production, changes in socioeconomics, and political thinking of modern society, has enabled this dire prophesy to remain unfulfilled.

Unfortunately, the technological advances in the 20th century primarily benefited the industrial countries, leaving widespread hunger and malnutrition to persist in most developing countries. Many of these nations depend on food aid from industrial countries for survival. In 1967, a report by the US President's Science Advisory Committee came to the grim conclusion that "the scale, severity and duration of the world food problem are so great that a massive, long-range, innovative effort unprecedented in human history will be required to master it". The Rockefeller and Ford Foundations, acting on this challenge, proceeded to establish the first international agricultural system to help transfer the agricultural technologies of the developed countries to the developing countries. These humble beginnings led to a dramatic impact on food production in the third world, especially Asia, which would be dubbed the Green Revolution, a term coined in 1968 by the USAID Administrator, William S. Gaud.

The Green Revolution started in 1943 when the Mexican government and the Rockefeller Foundation co-sponsored a project, the Mexican Agricultural Program, to increase food production in Mexico. The first target crop was wheat, and the goal was to increase wheat production by a large margin. Using an interdisciplinary approach, the scientific team headed by Norman Borlaug, a wheat breeder at the Rockefeller Foundation, started to assemble genetic resources (germplasm) of wheat from all over the world (East Africa, Middle East, South Asia, Western Hemisphere). The key genotypes used by Norman Borlaug in his breeding program were the Japanese "Norin" dwarf genotypes supplied by Burton Bayles of the United States Department of Agriculture (USDA) and a segregating ( $F_2$ ) population of "Norin 10" crossed with "Brevor", a Pacific Northwest wheat, supplied by Orville Vogel of the USDA. These introductions were crossed with indigenous (Mexican) wheat that had adaptability (to temperature, photoperiod) to the region and were disease resistant, but were low yielding and prone to lodging. The team was able to develop lodging-resistant cultivars through introgression of dwarf genes from semidwarf cultivars from North America. This breakthrough occurred in 1953. Further crossing and selection resulted in the release of the first Mexican semidwarf cultivars, "Penjamo 62" and "Pitic 62". Together with other cultivars, these two hybrids dramatically transformed wheat yields in Mexico, eventually making Mexico a major wheat exporting country. The successful wheat cultivars were introduced into Pakistan, India, and Turkey in 1966, with similar results of outstanding performance. During the period, wheat production increased from 300,000 to 2.6 million tons/year; yields per unit area increased from 750 to 3,200 kg/ha.

The Mexican model (interdisciplinary approach, international team effort) for agricultural transformation was duplicated in rice in the Philippines in 1960. This occurred at the IRRI. The goal of the IRRI team was to increase productivity of rice in the field. Rice germplasm was assembled. Scientists determined that, like wheat, a dwarf cultivar that was resistant to lodging, amenable to high density crop stand, responsive to fertilization and highly efficient in partitioning of photosynthates or dry matter to the grain, was the cultivar to breed.

In 1966, the IRRI released a number of dwarf rice cultivars to farmers in the Philippines. The most success was realized with IR8, which was early maturing (120 days), thus allowing double cropping in certain regions. The key to the high yield of the IR series was their



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## Industry highlights

### *Normal Ernest Borlaug: the man and his passion*

*For more than half a century, I have worked with the production of more and better wheat for feeding the hungry world, but wheat is merely a catalyst, a part of the picture. I am interested in the total development of human beings. Only by attacking the whole problem can we raise the standard of living for all people, in all communities, so that they will be able to live decent lives. This is something we want for all people on this planet.*

**Norman E. Borlaug**

Dr Norman E. Borlaug has been described in the literature in many ways, including as “the father of the Green Revolution”, “the forgotten benefactor of humanity”, “one of the greatest benefactors of human race in modern times”, and “a distinguished scientist-philosopher”. He has been presented before world leaders and received numerous prestigious academic honors from all over the world. He belongs to an exclusive league with the likes of Henry Kissinger, Elie Wiesel, and President Jimmy Carter – all Nobel Peace laureates. Yet, Dr Borlaug is hardly a household name in the USA. But, this is not a case of a prophet being without honor in his country. It might be more because this outstanding human being chooses to direct the spotlight on his passion, rather than his person. As previously stated in his own words, Dr Borlaug has a passion for helping to achieve a decent living status for the people of the world, starting with the alleviation of hunger. To this end, his theatre of operation is the third world countries, which are characterized by poverty, political instability, chronic food shortages, malnutrition, and the prevalence of preventable diseases. These places are hardly priority sources for news for the first world media, unless an epidemic or catastrophe occurs.

Dr Borlaug was born on March 25, 1914, to Henry and Clara Borlaug, Norwegian immigrants in the city of Saude, near Cresco, Iowa. He holds a BS degree in Forestry, which he earned in 1937. He pursued an MS in Forest Pathology, and later earned a PhD in Pathology and Genetics in 1942 from the University of Minnesota. After a brief stint with the E. I. du Pont de Nemours in Delaware, Dr Borlaug joined the Rockefeller Foundation team in Mexico in 1944, a move that would set him on course to achieve one of the most notable accomplishments in history. He became the director of the Cooperative Wheat Research and Production Program in 1944, a program initiated to develop high-yielding cultivars of wheat for producers in the area.

In 1965, the Centro Internacional de Mejoramiento de Maíz y Trigo (CIMMYT) was established in Mexico, as the second of the currently 16 International Agricultural Research Centers (IARCs) by the Consultative Group on International Agricultural Research (CGIAR). The purpose of the center was to undertake wheat and maize research to meet the production needs of developing countries. Dr Borlaug served as the director of the Wheat Program at CIMMYT until 1979 when he retired from active research, but not until he had accomplished his landmark achievement, dubbed the Green Revolution. The key technological strategies employed by Dr Borlaug and his team were to develop high-yielding varieties of wheat, and an appropriate agronomic package (fertilizer, irrigation, tillage, pest control) for optimizing the yield potential of the varieties. Adopting an interdisciplinary approach, the team assembled germplasm of wheat from all over the world. Key contributors to the efforts included Dr Burton Bayles and Dr Orville Vogel, both of the USDA, who provided the critical genotypes used in the breeding program. These genotypes were crossed with Mexican genotypes to develop lodging-resistant, semidwarf wheat varieties that were adapted to the Mexican production region (Figure 1). Using the improved varieties and appropriate agronomic packages, wheat production in Mexico increased dramatically from its low 750 kg/ha to about 3,200 kg/ha. The successful cultivars were introduced into other parts of the world, including Pakistan, India, and Turkey in 1966, with equally dramatic results. So successful was the effort in wheat that the model was duplicated in rice in the Philippines in 1960. In 1970, Dr Norman Borlaug was honored with the Nobel Peace Prize for contributing to curbing hunger in Asia and other parts of the world where his improved wheat varieties were introduced (Figure 2).

Whereas the Green Revolution was a life-saver for countries in Asia and some Latin American countries, another part of the world that is plagued by periodic food shortages, the sub-Saharan Africa, did not benefit from this event. After retiring from CIMMYT in 1979, Dr Borlaug focused his energies on alleviating hunger and promoting the general well-being of the people on the continent of Africa. Unfortunately, this time around, he had to go without the support of these traditional allies, the Ford Foundation, the Rockefeller Foundation, and the World Bank. It appeared the activism of powerful environmental groups in the developed world had managed to persuade these donors from supporting what, in their view, was an environmentally intrusive practice advocated by people such as Dr Borlaug. These environmentalists promoted the notion that high-yield agriculture for Africa, where the agronomic package included inorganic fertilizers, would be ecologically disastrous.

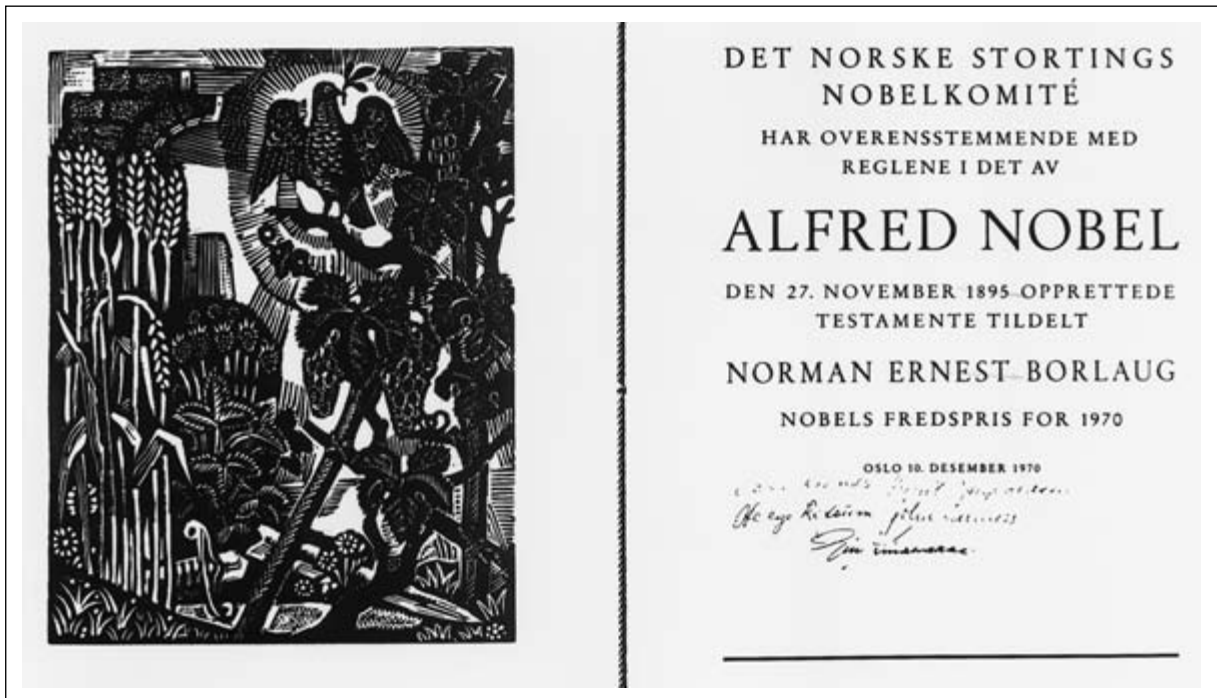
Incensed by the distractions of “green politics”, which sometimes is conducted in an elitist fashion, Dr Borlaug decided to press on undeterred with his passion to help African farmers. At about the same time, President Jimmy Carter was collaborating with the



**Figure 1** Dr Norman Borlaug working in a wheat crossing block.

late Japanese industrialist, Ryoichi Sasakawa, in addressing some of the same agricultural issues dear to Dr Borlaug. In 1984, Mr Sasakawa persuaded Dr Borlaug to come out of retirement to join them to vigorously pursue food production in Africa. This alliance gave birth to the Sasakawa Africa Association, presided over by Dr Borlaug. In conjunction with Global 2000 of The Carter Center, Sasakawa-Global 2000 was born, with a mission to help small-scale farmers to improve agricultural productivity and crop quality in Africa. Without wasting time, Dr Borlaug selected an initial set of countries in which to run projects. These included Ethiopia, Ghana, Nigeria, Sudan, Tanzania, and Benin (Figure 3). The crops targeted included popular staples such as corn, cassava, sorghum, and cowpeas, as well as wheat. The most spectacular success was realized in Ethiopia, where the country recorded its highest ever yield of major crops in the 1995–1996 growing season.

Sasakawa-Global 2000 operates in some 12 African nations. Dr Borlaug is still associated with CIMMYT and also holds a faculty position at Texas A&M University, where he teaches international agriculture in the fall semester. On March 29, 2004, in commemoration of his 90th birthday, Dr Borlaug was honored by the USDA with the establishment of the Norman E. Borlaug International Science and Technology Fellowship Program. The fellowship is designed to bring junior and mid-ranking scientists and policy-makers from African, Asian, and Latin American countries to the United States to learn from their US counterparts.



**Figure 2** A copy of the actual certificate presented to Dr Norman Borlaug as part of the 1970 Nobel Peace Prize Award he received.



**Figure 3** Dr Twumasi Afriyie, CIMMYT Highland Maize Breeder and a native of Ghana, discusses the quality protein maize he was evaluating in a farmer's field in Ghana with Dr Borlaug.

### *Further reading*

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responsiveness to heavy fertilization. The short, stiff stalk of the improved dwarf cultivar resisted lodging under heavy fertilization. Unimproved indigenous genotypes experienced severe lodging under heavy fertilization, resulting in drastic reduction in grain yield.

Similarly, cereal production in Asia doubled between 1970 and 1995, as the population increased by 60%. Unfortunately, the benefits of the Green Revolution barely reached sub-Saharan Africa, a region of the world with perennial severe food shortages, partly because of the lack of appropriate infrastructure and limited resources. Dr Norman Borlaug received the 1970 Nobel Prize for Peace for his efforts at curbing global hunger.

Three specific strategies were employed in the Green Revolution:

- 1 Plant improvement.** The Green Revolution centered on the breeding of high-yielding, disease-resistant, and environmentally responsive (adapted, responsive to fertilizer, irrigation, etc.) cultivars.
- 2 Complementary agronomic package.** Improved cultivars are as good as their environment. To realize the full potential of the newly created genotype, a certain production package was developed to com-

plement the improved genotype. This agronomic package included tillage, fertilization, irrigation, and pest control.

### **3 Favorable returns on investment in technology.**

A favorable ratio between the cost of fertilizer and other inputs and the price the farmer received for using this product was an incentive for farmers to adopt the production package.

Not unexpectedly, the Green Revolution has been the subject of some intensive discussion to assess its sociological impacts and identify its shortcomings. Incomes of farm families were raised, leading to an increase in demand for goods and services. The rural economy was energized. Food prices dropped. Poverty declined as agricultural growth increased. However, critics charge that the increase in income was inequitable, arguing that the technology package was not scale neutral (i.e., owners of larger farms were the primary adopters because of their access to production inputs – capital, seed, irrigation, fertilizers, etc.). Furthermore, the Green Revolution did not escape the accusations often leveled at high-yielding agriculture – environmental degradation from improper or excessive use of

agrochemicals. Recent studies have shown that many of these charges are overstated.

### Future of plant breeding in society

For as long as the world population is expected to continue to increase, there will continue to be a demand for more food. However, with an increasing population comes an increasing demand for land for residential, commercial, and recreational uses. Sometimes, farm lands are converted to other uses. Increased food production may be achieved by increasing production per unit area or bringing new lands into cultivation. Some of the ways in which society will affect and be affected by plant breeding in the future are as follow:

- 1 **New roles of plant breeding.** The traditional roles of plant breeding (food, feed, fiber, and ornamentals) will continue to be important. However, new roles are gradually emerging for plants. The technology for using plants as bioreactors to produce pharmaceuticals will advance; this technology has been around for over a decade. Strategies are being perfected for use of plants to generate pharmaceutical antibodies, engineering antibody-mediated pathogen resistance, and altering plant phenotypes by immunomodulation. Successes that have been achieved include the incorporation of *Streptococcus* surface antigen in tobacco, and the herpes simplex virus in soybean and rice.
- 2 **New tools for plant breeding.** New tools will be developed for plant breeders, especially, in the areas of the application of biotechnology to plant breeding. New marker technologies continue to be developed and older ones advanced. Tools that will assist breeders to more effectively manipulate quantitative traits will be enhanced.
- 3 **Training of plant breeders.** As discussed elsewhere in the book, plant breeding programs have experi-

enced a slight decline in graduates in recent past. Because of the increasing role of biotechnology in plant genetic manipulation, graduates who combine skills and knowledge in both conventional and molecular technologies are in high demand. It has been observed that some commercial plant breeding companies prefer to hire graduates with training in molecular genetics, and then provide them with the needed plant breeding skills on the job.

- 4 **The key players in plant breeding industry.** The last decade saw a fierce race by multinational pharmaceutical corporations to acquire seed companies. There were several key mergers as well. The modern technologies of plant breeding are concentrated in the hands of a few of these giant companies. The trend of acquisition and mergers are likely to continue in the future.
- 5 **Yield gains of crops.** With the dwindling of arable land and the increase in policing of the environment by activists, there is an increasing need to produce more food or other crop products on the same piece of land in a more efficient and environmentally safer manner. High-yielding cultivars will continue to be developed, especially in crops that have received less attention from plant breeders. Breeding for adaptation to environmental stresses (e.g., drought, salt) will continue to be important, and will enable more food to be produced on marginal lands.
- 6 **The biotechnology debate.** It is often said that these modern technologies for plant genetic manipulation benefit the developing countries the most since they are in dire need of food, both in quantity and nutritional value. On the other hand, the intellectual property that covers these technologies is owned by the giant multinational corporations. Efforts will continue to be made to negotiate fair use of these technologies. Appropriate technology transfer and support to the poor third world nations will continue, to enable them to develop capacity for the exploitation of these modern technologies.

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## Outcomes assessment

### Part A

Please answer the following questions true or false:

- 1 Plant breeding causes permanent changes in plant heredity.
- 2 Rice varieties were the first products of the experiments leading to the Green Revolution.
- 3 Rice is high in pro-vitamin A.
- 4 The IR8 was the rice variety released as part of the Green Revolution.
- 5 Wilhelm Johannsen developed the pure-line theory.

### Part B

Please answer the following questions:

- 1 ..... won the Nobel Peace Prize in ..... for being the chief architect of the .....
- 2 Define plant breeding.
- 3 Give three specific objectives of plant breeding.
- 4 Discuss plant breeding before Mendel's work was discovered.
- 5 Give the first two major wheat cultivars to come out of the Mexican Agricultural Program initiated in 1943.

### Part C

Please write a brief essay on each of the following topics:

- 1 Plant breeding is an art and a science. Discuss.
- 2 Discuss the importance of plant breeding to society.
- 3 Discuss how plant breeding has changed through the ages.
- 4 Discuss the role of plant breeding in the Green Revolution.
- 5 Discuss the impact of plant breeding on crop yield.
- 6 Plant breeding is critical to the survival of modern society. Discuss.