1 Introduction

Purpose and expected outcomes

Agriculture *is the deliberate planting and harvesting of plants and herding animals. This human invention has and continues to impact 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. This introductory chapter is devoted to presenting a brief overview of plant breeding, including its benefits to society and some historical perspectives. After completing this chapter, the student should have a general understanding of:*

1. The need and importance of plant breeding to society.
2. The goals of plant breeding.
3. The art and science of plant breeding.
4. Trends in plant breeding as an industry.
5. Selected milestones and accomplishments of plant breeders.
6. The future of plant breeding in society.

1.1 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

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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 readily 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 food crops (e.g., vegetables), ornamentals (e.g., roses, pine trees), fruit trees (e.g., citrus, apple), forage crops (e.g., alfalfa, grasses), or turf species. (e.g., Bluegrass, fescue) More importantly, breeders tend to specialize in or focus on specific species in these groups (e.g., corn breeder, potato breeder). 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 plant species.

1.2 The 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 will resist lodging and thereby facilitate mechanical harvesting. They may develop plants that resist pests, so that the farmer does not have to apply pesticides, or applies 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, rickettsia) caused by the consumption of nutrient-deficient foods, as pertains 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., high oleic content 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 in the past 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, plant breeders 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.

1.3 The concept of genetic manipulation of plant attributes

The work of Gregor Mendel and further advances in science that followed his discoveries established that plant traits 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). While 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 selected 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).

1.4 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.

1.4.1 Addressing world food and feed quality 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 nonliving 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).

Table 1.1 Twenty five major food crops of the world.

1	Wheat	11	Sorghum	21	Apples
2	Rice	12	Sugarcane	22	Yam
3	Corn	13	Millets	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	Grapes	18	Oranges		
9	Soybean	19	Coconut		
10	Oats	20	Cottonseed oil		

The ranking is according to total tonnage produced annually. (Source: Harlan, 1976)

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 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 (Golden rice 2, with a 20-fold increase in pro-vitamin A, has been developed by Syngenta's Jealott's Hill International Research Centre in Berkshire, UK). An estimated 800 million people in the world, including 200 million children, suffer chronic under-nutrition, 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, amongst other things, in improving feed quality (high digestibility, high nutritional profile) for livestock.

1.4.2 Addressing food supply 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 three 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 aligned with population growth. Unfortunately, land for farming is scarce. Farmers have expanded their enterprise onto new lands. Further expansion is a challenge because land that can be used for farming is now being used for commercial and residential purposes to meet the demands of a growing population. Consequently, more food will have to be produced on less land. This calls for improved and high yielding cultivars 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 the people are already most severely strained, because of natural or human-made disasters, or ineffective political systems.

1.4.3 Need to adapt plants to environmental stresses

The phenomenon of global climatic change that is occurring 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), poorer countries are easily devastated by even brief episodes of adverse weather conditions. For example, 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 and 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). Development of photoperiod insensitive crop cultivars would allow an expansion in production of previously photoperiod sensitive species.

1.4.4 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.

1.4.5 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.

1.4.6 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 for 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 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, potato is a versatile crop used for food and industrial products. Different varieties are being developed by breeders for baking, cooking, fries (frozen), chipping, and starch. These cultivars differ in size, specific gravity, and sugar content, among other properties. High sugar content is undesirable for frying or chipping because the sugar caramelizes under high heat to produce undesirable browning of fries and chips.

1.5 Overview of the basic steps in plant breeding

Plant breeding has come a long way, from the cynical view of "crossing the best with best and hoping for the best" to carefully planned and thought-out strategies to develop high performance cultivars. Plant breeding methods and tools keep changing as technology advances. Consequently, plant breeding approaches may be categorized into two general types: **conventional** and **unconventional**. (This categorization is only for convenience.)

- **Conventional approach.** Conventional breeding is also referred to as **traditional** or **classical breeding**. This approach entails the use of tried, proven, and older tools. Crossing two plants (hybridization) is the primary technique for creating variability in flowering species. Various breeding methods are then used to discriminate among the variability (selection) to identify the most desirable recombinant. The selected genotype is increased and evaluated for performance before release to producers. Plant traits controlled by many genes (quantitative traits) are more difficult to breed. Age notwithstanding, the conventional approach remains the workhorse of the plant breeding industry. It is readily accessible to the average breeder and is relatively easy to conduct compared to the unconventional approach.
- **Unconventional approach.** The unconventional approach to breeding entails the use of cutting edge technologies for creating new variability that it is sometimes impossible to achieve with conventional methods. However, this approach is more involved, requiring special technical skills and knowledge. It is also expensive to conduct. The advent of recombinant DNA (rDNA) technology gave breeders a new set of powerful tools for genetic analysis and manipulation. Gene transfer can now be made across natural biological barriers, circumventing the sexual process (e.g., the *Bt* products that consist of bacterial genes transferred into crops to confer resistance to the European corn borer). Molecular markers are available to aid the selection process to make the process more efficient and effective.

Even though two basic breeding approaches have been described, it should be pointed out that they are best considered as complementary rather than independent approaches. Usually, the molecular tools are used to generate variability for selection, or to facilitate the selection process. After genetically modifying plants using molecular tools, it may be used as a parent in subsequent crosses, using conventional tools, to transfer the desirable genes into adapted and commercially desirable genetic backgrounds. Whether developed by conventional or molecular approaches, the genotypes are evaluated in the field by conventional methods and then advanced through the standard seed certification process before the farmer can have access to it for planting a crop. The unconventional approach to breeding tends to receive more attention from funding agencies than the conventional approach, partly because of its novelty and advertised potential, as well as the glamour of the technologies involved.

Regardless of the approach, a breeder follows certain general steps in conducting a breeding project. A breeder should have a comprehensive plan for a breeding project that addresses:

- **Objectives.** The breeder should first define a clear objective (or set of objectives) for initiating the breeding program. In selecting breeding objectives, breeders need to consider:
  (a) The producer (grower) from the point of view of growing the cultivar profitably (e.g., need for high yield, disease resistance, early maturity, lodging resistance).
  (b) The processor (industrial user) as it relates to efficiently and economically using the cultivar as raw materials for producing new product (e.g., canning qualities, fiber strength).
  (c) The consumer (household user) preference (e.g., taste, high nutritional quality, shelf life).

The tomato will be used to show how different breeding objectives can be formulated for a single crop. Tomato is a very popular fruit with a wide array of uses, each calling for certain qualities. For salads, tomato is used whole, and hence the small size is preferred; for hamburgers, tomato is sliced, round large fruits being preferred. Tomato for canning (e.g., puree) requires certain pulp qualities. Being a popular garden species, gardeners prefer a tomato cultivar that ripens over time so harvesting can be spaced. However, for industrial use, as in the case of canning, the fruits on the commercial cultivar must ripen together, so the field can be mechanically harvested. Furthermore, whereas appearance of the fruit is not top priority for a processor who will be making tomato juice, the appearance of fruits is critical in marketing the fruit for table use.

- **Germplasm.** It is impossible to improve plants or develop new cultivars without genetic variability. Once the objectives have been determined, the breeder then assembles the germplasm to be used to initiate the breeding program. Sometimes, new variability is created through crossing of selected parents, inducing mutations, or using biotechnological techniques. Whether used as such or recombined through crossing, the base population used to initiate a breeding program must of necessity include the gene(s) of interest. That is, you cannot breed for disease resistance, if the gene conferring resistance to the disease of interest does not occur in the base population.
- **Selection.** After creating or assembling variability, the next task is to discriminate among the variability to identify and select individuals with the desirable genotype to advance and increase in order to develop potential new cultivars. This calls for using standard selection or breeding methods suitable for the species and the breeding objective(s).
- **Evaluation.** Even though breeders follow basic steps in their work, the product reaches the consumer only after it has been evaluated. Agronomists may participate in this stage of plant breeding. In a way, evaluation is also a selection process, for it entails comparing a set of superior candidate genotypes to select one for release as a cultivar. The potential cultivars are evaluated in the field, sometimes at different locations and over several years, to identify the most promising one for release as a commercial cultivar.
- **Certification and cultivar release.** Before a cultivar is released, it is processed through a series of steps, called the seed certification process, to increase the experimental seed and to obtain approval for release from the designated crop certifying agency in the state or country. These steps in plant breeding are discussed in detail in this book.

1.6 How have plant breeding objectives changed over the years?

In a review of plant breeding over the past 50 years, Baenzinger and colleagues in 2006 revealed that while some aspects of how breeders conduct their operations have dramatically changed, others have stubbornly remained the same, being variations on a theme at best.

Breeding objectives in the 1950s and 1960s, and before, appeared to focus on increasing crop productivity. Breeders concentrated on yield and adapting crops to their production environment. Resistance to diseases and pests was also priority. Quality traits for major field crops, such as improved fiber strength for cotton and milling and baking quality in wheat, were important in the early breeding years. Attention was given to resistance to abiotic stresses such as winter hardiness and traits like lodging resistance, uniform ripening, and seed oil content of some species. Crop yield continued to be important throughout the 1990s. However, as analytical instrumentation that allowed high throughput, low cost, ease of analysis and repeatability of results became more readily available, plant breeders began to include nutritional quality traits into their breeding objectives. These included forage quality traits, such as digestibility and neutral detergent fiber.

More importantly, with advanced technology, quality traits are becoming more narrowly defined in breeding objectives. Rather than high protein or high oil, breeders are breeding for specifics, such as low linolenic acid content, to meet consumer preferences for eating healthful foods (low linolenic acid in oil provides it with stability and enhanced flavor, and reduces the need for partial hydrogenation of the oil and production of trans fatty acids). Also, a specific quality trait such as low phytate phosphorus in grains (e.g., corn, soybean) would increase feed efficiency and reduce phosphorus in animal waste, a major source of the environmental degradation of lakes.

Perhaps no single technology has impacted breeding objectives more in recent times than biotechnology (actually, a collection of biological technologies). The subject is discussed in detail in later chapters. Biotechnology has enabled breeders to develop a new generation of cultivars with genes included from genetically unrelated species (transgenic or GM cultivars). The most successful transgenic input traits to date have been herbicide resistance and insect resistance, which have been incorporated into major crops species like corn, cotton, soybean, and tobacco. According to a 2010 International Service for the Acquisition of Agri-Biotech Crops (ISAAA) report, GM is far from being a global industry, with only six countries (USA, Brazil, Argentina, India, Canada and China) growing about 95% of the total global acreage (use leads with about 50%). Some argue that biotechnology has become the tail that wags the plant breeding industry. Improvement in plant genetic manipulation technology has also encouraged the practice of gene stacking in plant breeding. Another significant contribution of biotechnology to changing breeding objectives is the creation of the "universal gene pool", whereby breeders, in theory, have limitless sources of diversity, and hence can be more creative and audacious in formulating breeding objectives.

In the push to reduce our carbon footprint and reduce environmental pollution, there is a drive towards the discovery and use of alternative fuel sources. Some traditional improvement of some crop species (e.g., corn) for food and feed is being changed to focus some attention on their industrial use, through increasing biomass for biofuel production, and as bioreactors for production of polymers and pharmaceuticals. In terms of reducing adverse environmental impact, one of the goals of modern breeding is to reduce the use of agrochemicals.

1.7 The art and science of plant breeding

The early domesticators relied solely on experience and intuition to select and advance plants they thought had superior qualities. As knowledge abounds and technology advances, modern breeders are increasingly depending on science to take the guesswork out of the selection process, or at least reduce it. At the minimum, a plant breeder should have a good understanding of genetics and the principles and concepts of plant breeding, hence the emphasis of both disciplines in this book. Students taking a course in plant breeding are expected to have taken at least an introductory course in genetics. Nonetheless, two supplementary chapters have been provided in this book; they review some pertinent genetic concepts that will aid the student in understanding plant breeding. By placing these fundamental concepts in the back of the book, users will not feel obligated to study them but can use them on as needed basis.

1.7.1 Art and the concept of the "breeder's eye"

Plant breeding is an applied science. Just like other non-exact science disciplines or fields, art is important to the success achieved by a plant breeder. Early plant breeders depended primarily on intuition, skill, and judgment in their work. These attributes are still desirable in modern day plant breeding. This book discusses the various tools available to plant breeders. Plant breeders may use different tools to tackle the same problem, the results being the arbiter of the wisdom in the choices made. In fact, it is possible for different breeders to use the same set of tools to address the same kind of problem with different results, due in part to the differences in their skill and experience. As is discussed later in the book, some breeding methods depend on phenotypic selection (based on appearance; visible traits). This calls for the proper design of the fieldwork to minimize the misleading effect of a variable environment on the expression of plant traits. Selection may be likened to a process of informed "eye-balling" to discriminate among variability.

A good breeder should have a keen sense of observation. Several outstanding discoveries were made just because the scientists who were responsible for these events were observant enough to spot unique and unexpected events. Luther Burbank selected one of the most successful cultivars of potato, the "Burbank potato", from among a pool of variability. He observed a seed ball on a vine of the "Early Rose" cultivar in his garden. The ball contained 23 seeds, which he planted directly in the field. At harvest time the following fall, he dug up and kept the tubers from the plants separately. Examining them, he found two vines that were unique, bearing large smooth and white potatoes. Still, one was superior to the others. The superior one was sold to a producer who named it Burbank. The Russet Burbank potato is produced on about 50% of all lands devoted to potato production in the United States.

Breeders often have to discriminate among hundreds and even tens of thousands of plants in a segregating population to select only a small fraction of promising plants to advance in the program. Visual selection is an art, but it can be facilitated by selection aids such as **genetic markers** (simply inherited and readily identified traits that are linked to desirable traits that are often difficult to identify). Morphological markers (not biochemical markers) are useful when visual selection is conducted. A keen eye is advantageous even when markers are involved in the selection process. As is emphasized later in this book, the breeder ultimately adopts a holistic approach to selection, evaluating the overall worth or desirability of the genotype, not just the trait targeted in the breeding program.

1.7.2 The scientific disciplines and technologies of plant breeding

The science and technology component of modern plant breeding is rapidly expanding. While a large number of science disciplines directly impact plant breeding, several are closely associated with it. These are plant breeding, genetics, agronomy, cytogenetics, molecular genetics, botany, plant physiology, biochemistry, plant pathology, entomology, statistics, and tissue culture. Knowledge of the first three disciplines is applied in all breeding programs. The technologies used in modern plant breeding are summarized in Table 1.2. These technologies are discussed in varying degrees in this book. The categorization is only approximate and generalized. Some of these tools are used to either generate variability directly or to transfer genes from one genetic background to another to create variability for breeding. Some technologies facilitate the breeding process through, for example, identifying individuals with the gene(s) of interest.

- **Genetics.** Genetics is the principal scientific basis of modern plant breeding. As previously indicated, plant breeding is about targeted genetic modification of plants. The science of genetics enables plant breeders to predict, to varying extents, the outcome of genetic manipulation of plants. The techniques and methods employed in breeding are determined based on the genetics of the trait of interest, regarding, for example, the number of genes coding for it and gene action. For example, the size of the segregating population to generate in order to have a

Table 1.2 An operational classification of technologies of plant breeding.

Classical/traditional tools	**Common use of the technology/tool**
Emasculation	making a completer flower female; preparation for crossing
Hybridization	crossing un-identical plants to transfer genes or achieve recombination
Wide crossing	crossing of distantly related plants
Selection	the primary tool for discriminating among variability
Chromosome counting	determination of ploidy characteristics
Chromosome doubling	manipulating ploidy for fertility
Male sterility	to eliminate need for emasculation in hybridization
Triploidy	to achieve seedlessness
Linkage analysis	for determining association between genes
Statistical tools	for evaluation of germplasm
Relatively advanced tools	
Mutagenesis	to induce mutations to create new variability
Tissue culture	for manipulating plants at the cellular or tissue level
Haploidy	used to create extremely homozygous diploid
Isozyme markers	to facilitate the selection process
In situ hybridization	detect successful interspecific crossing
More sophisticated tools	
DNA markers	
– RFLP	more effective than protein markers (isozymes)
– RAPD	PCR-based molecular marker
Advanced technology	
Molecular markers	SSR, SNPs, etc.
Marker assisted selection	facilitate the selection process
DNA sequencing	ultimate physical map of an organism
Plant genomic analysis	studying the totality of the genes of an organism
Bioinformatics	computer-based technology for prediction of biological function from DNA sequence data
Microarray analysis	to understand gene expression and for sequence identification
Primer design	for molecular analysis of plant genome
Plant transformation	for recombinant DNA work

chance of observing that unique plant with the desired combination of genes, depends on the number of genes involved in the expression of the desired trait.

- **Botany.** Plant breeders need to understand the reproductive biology of their plants as well as their taxonomic attributes. They need to know if the plants to be hybridized are cross-compatible, as well as to know in fine detail about flowering habits, in order to design the most effective crossing program.
- **Plant physiology.** Physiological processes underlie the various phenotypes observed in plants. Genetic manipulation alters plant physiological performance, which in turn impacts the plant performance in terms of the desired economic product. Plant breeders manipulate plants for optimal physiological efficiency, so that dry matter is effectively partitioned in favor of the economic yield. Plants respond to environmental factors, biotic (e.g., pathogens) and abiotic (e.g., temperature, moisture). These factors are sources of physiological stress when they occur at unfavorable levels. Plant breeders need to understand these stress relationships in order to develop cultivars that can resist them for enhanced productivity.
- **Agronomy.** Plant breeders conduct their work in both controlled (greenhouse) and field environments. An understanding of agronomy (the art and science of producing crops and managing soils) will help the breeder to provide the appropriate cultural conditions for optimal plant growth and development for successful hybridization and selection in the field. An improved cultivar is only as good as its cultural environment. Without the proper nurturing, the genetic potential of an improved cultivar would not be realized. Sometimes, breeders need to modify the plant growing environment to identify individuals to advance in a breeding program to achieve an objective (e.g., withholding water in breeding for drought resistance).
- **Pathology and entomology.** Disease resistance breeding is a major plant breeding objective. Plant breeders need to understand the biology of the insect pest or pathogen against which resistance is being sought. The kind of cultivar to breed, the methods to use in breeding and evaluation all depend on the kind of pest or pathogen (e.g., its races or variability, pattern of spread, life cycle, and most suitable environment).
- **Statistics.** Plant breeders need to understand the principles of research design and analysis. This knowledge is essential for effectively designing field and laboratory studies (e.g., for heritability, inheritance of a trait, combining ability) and for evaluating genotypes for cultivar release at the end of the breeding program. Familiarity with computers is important for record keeping and data manipulation. Statistics is indispensable to plant breeding programs. This is because the breeder often encounters situations in which predictions about outcomes, comparison of results, estimation of response to a treatment, and many more, need to be made. Genes are not expressed in a vacuum but in an environment with which they interact. Such interactions may cause certain outcomes to deviate from the expected. Statistics is needed to analyze the variance within a population to separate real genetic effects from environmental effects. Application of statistics in plant breeding can be as simple as finding the mean of a set of data, to complex estimates of variance and multivariate analysis.
- **Biochemistry.** In this era of biotechnology, plant breeders need to be familiar with the molecular basis of heredity. They need to be familiar with the procedures of plant genetic manipulation at the molecular level, including the development and use of molecular markers and gene transfer techniques.

While the training of a modern plant breeder includes these courses and practical experiences in these and other disciplines, it is obvious that the breeder cannot be an expert in all of them. Modern plant breeding is more *team work* than solo effort. A plant breeding team will usually have experts in all these key disciplines, each one contributing to the development and release of a successful cultivar.

1.8 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.

1.8.1 Yield increase

Yield increase in crops has been accomplished in a variety of ways, including targeting yield *per se* or its

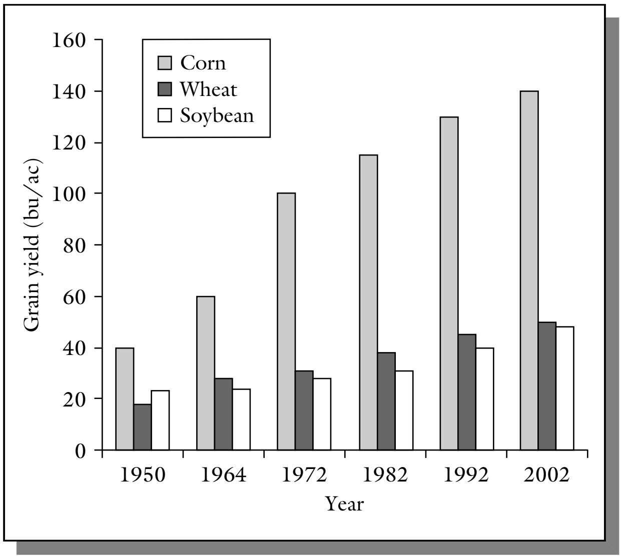

Figure 1.1 The yield of major world food crops is steadily rising, as indicated by the increasing levels of crops produced in the US agricultural system. A significant portion of this rise is attributable to the use of improved crop cultivars by crop producers. (Source: Drawn with data from the USDA.)

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, and soybean) have significantly increased in the USA over the years (Figure 1.1). For example, the yield of corn rose from about 2000 kg/ha in the 1940s to about 7000 kg/ha in the 1990s. In England, it took only 40 years for wheat yields to rise from 2 metric tons/ha to 6 metric tons/ha. Food and Agriculture Organization (FAO) data comparing crop yield increases between 1961 and 2000 show dramatic changes for different crops in different regions of the of the world. For example, wheat yield increased by 681% in China, 301% in India, 299% in Europe, 235% in Africa, 209% in South America, and 175% in the USA. These yield increases are not totally due to the genetic potential of the new crop cultivars (about 50% is attributed to plant breeding) but are also due to the 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.

1.8.2 Enhancement of compositional traits

Breeding for plant compositional traits to enhance nutritional quality or meet an industrial need are major plant breeding goals. High protein crop varieties (e.g., high lysine or quality protein maize) have been produced for use in various parts of the world. 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; 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.

1.8.3 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 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; 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.

1.8.4 Impact on crop production systems

Crop productivity is a function of the genotype (genetic potential of the cultivar) and the cultural environment. The **Green Revolution** is an example of an outstanding outcome of the combination of plant breeding efforts and production technology to increase food productivity. A chemically intensive production system (use of agrochemicals-like fertilizers) calls for crop cultivars that are responsive to such high input growing conditions. Plant breeders have developed cultivars with the architecture for such environments. Through the use of genetic engineering technology, breeders have reduced the need for pesticides in the production of major crops (e.g., corn, tobacco, soybean) with the development of GM pest resistant cultivars, thereby reducing environmental damage from agriculture. Cultivars have been developed for mechanized production systems.

Industry highlights

Norman Ernest Borlaug: The man and his passion

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"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 United States. 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 spot light on his passion, rather than his person. As previously stated in his own words, Dr Borlaug has a passion for helping to achieve of 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 developing countries, which are characterized by poverty, political instability, chronic food shortages, malnutrition, and 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 accomplish 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 highyielding cultivars of wheat for producers in the area.

In 1965, the Centro Internationale de Mejoramiento de Maiz y Trigo (CIMMYT) was established in Mexico, as the second of the currently 16 International Agricultural Research Centers (IARC) 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, semi-dwarf wheat varieties that were adapted to the Mexican production region (Figure B1.1). Using the improved varieties and appropriate agronomic package, wheat production in Mexico increased dramatically from its low 750 kg/ha to about 3200 kg/ha. The successful cultivars were introduced into other part 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 B1.2).

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, whereby the agronomic package included inorganic fertilizers, would be ecologically disastrous.

Figure B1.1 Dr Norman Borlaug working in a wheat crossing block.

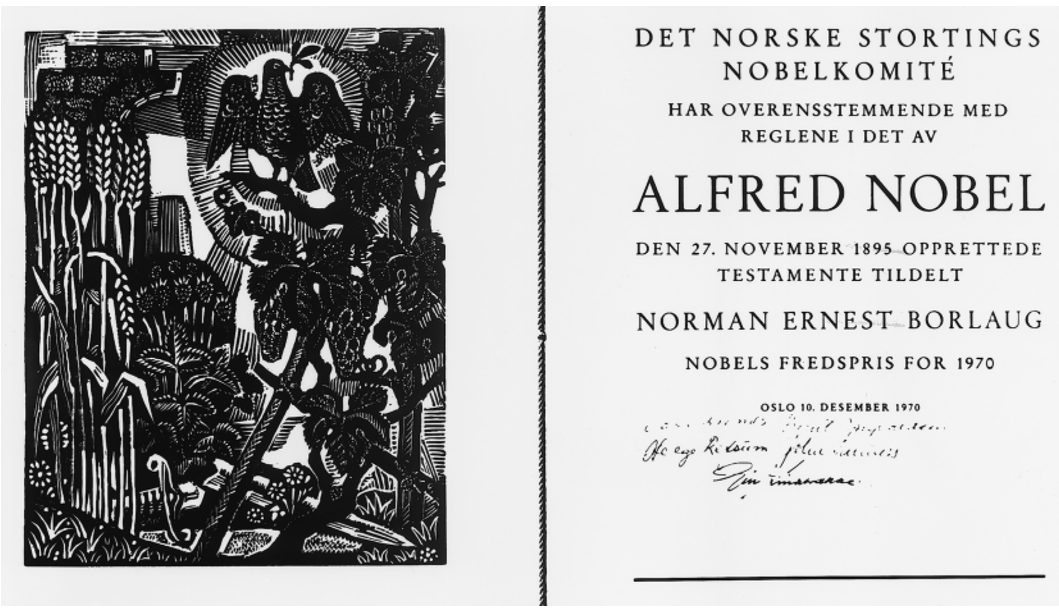

Figure B1.2 A copy of the actual certificate presented to Dr Norman Borlaug as part of the 1970 Nobel Peace Prize Award he received.

Figure B1.3 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.

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 late Japanese industrialist, Ryoichi Sasakawa, to address 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 the Global 2000 of The Carter Center, the 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 B1.3). The crops targeted included popular staples such as corn, cassava, sorghum, 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.

The Sasakawa-Global 2000 operates in some 12 African nations. Dr. Borlaug was associated with CIMMYT and also held a faculty position at Texas A&M University, where he taught international agriculture until his death on September 12, 2009. On March 29, 2004, in commemoration of his ninetieth 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 policymakers from African, Asian, and Latin American countries to the United States to learn from their US counterparts.

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1.9 The plant breeding industry

Commercial plant breeding is undertaken in both the private and public sectors. Breeding in the private sector is primarily for profit. A sample of the major plant breeding companies in the world is presented in Table 1.3. It should be pointed out these companies operate under the umbrella of giant multinational corporations, such as Monsanto, Pioneer/Dupont, Novartis/Syngenta, and Advanta Seed Group, through mergers and acquisitions. Products from private seed companies are proprietary. In the United

Table 1.3 Selected seed companies in various parts of the world.

Holland
Bakker Brothers
Bejo Zaden BV
De Ruiter Seeds
Pinnar Seed BV
Van Dijke Zaden
Enza Zaden BV
Nikerson-Zwaan BV
Germany
Hild Samen GmbH
Nikerson-Zwaan GmbH
United Kingdom
CN Seed Ltd.
Tozer Seeds
Nikerson-Zwaan GmbH
France
Clause
Panam Semences
Vilmorin
Technisem
Gautier Semences
South Africa
Capstone Seeds
Gellman Seeds Pty. Ltd.
JW Seeds
Pinnar Seed
Sensako
Kenya
Pinnar Seed
United States of America
Seminis
Syntenta Seeds
Monsanto
DeKalb
Danson Seeds
Campbell's Seed
Burpee
Pioneer

States, an estimated 65–75% of all plant breeders are employed in the private sector. More importantly, crop species that are self-pollinated (e.g., wheat), and hence allow farmers to save seed to plant the next season's crop, are of less interest to commercial seed breeders in the private sector. An estimated 80% of wheat breeders in the United States are in the public sector while only about 7% of corn (cross-pollinated, readily amenable to hybrid production) breeders are in the public sector. Most germplasm enhancement efforts (pre-breeding, introduction of exotic genes into cultivated germplasm) occur mainly in the public sector. Funds for public breeding in wheat come from contributions from the Wheat Growers Association.

The private sector dominates corn breeding throughout the industrial world. However, the roles of the public and private sectors differ markedly in Western Europe, different regions of the USA, Canada, and Australia, as outlined in the next sections.

1.9.1 Private sector plant breeding

Four factors are deemed by experts to be critical in determining the trends in investment in plant breeding by the private sector.

- **Cost of research innovation.** Modern plant breeding technologies are generally expensive to acquire and use. Consequently, the cost of research and development of new cultivars by these technologies are exorbitant. However, some of these innovations result in increased product quality and yield, and sometimes facilitate the production of the crop by the producer. Also, some innovations eventually reduce the duration of the cumulative research process.
- **Market structure.** Private companies are more likely to invest in plant breeding where the potential size of the seed market is large and profitable. Further, the attraction to enter into plant breeding will be greater if there are fixed costs in marketing the new cultivars to be developed.
- **Market organization of the seed industry.** Conventional wisdom suggests that the more concentrated a seed market, the greater the potential profitability a seed production enterprise would have. However, contemporary thought on industrial organization suggests that the ease of entry into an existing market would depend on the contestability of the specific market, and would subsequently decide the profitability to the company. Plant breeding is increasingly becoming a technology-driven industry. Through research and development, a breakthrough may grant a market monopoly to an inventor of a technology or product, until another breakthrough occurs that grants a new monopoly in a related market. For example, Monsanto, the developer of Roundup Ready® technology, is also the developer of the Roundup® herbicide, which is required for the technology to work.

- **Ability to appropriate the returns to research and distribution of benefits.** The degree to which a seed company can appropriate returns to its plant breeding inventions is a key factor in the decision to enter the market. Traditionally, cross-pollinated species (e.g., corn) that are amenable to hybrid breeding and high profitability have been most attractive to private investors. Public sector breeding develops most of the new cultivars in self-pollinated species (e.g., wheat, soybean). However, the private sector interest in self-pollinated species is growing. This shift is occurring for a variety of reasons. Certain crops are associated in certain cropping systems. For example, corn–soybean rotations are widely practiced. Consequently, producers who purchase improved corn are likely to purchase improved soybean seed. In the case of cotton, the shift is for a more practical reason. Processing cotton to obtain seed entails ginning and delinting, which are more readily done by seed companies than farmers.

  Another significant point that needs to be made is that the for-profit private breeding sector is obligated not to focus only on profitability of a product to the company, but it must also price its products such that the farmer can use them profitably. Farmers are not likely to adopt a technology that does not significantly increase their income!

1.9.2 Public sector plant breeding

The USA experience

Public sector breeding in the USA is conducted primarily by land grant institutions and researchers in the federal system (i.e., the United States Department of Agriculture (USDA)). The traditional land grant institutional program is centered on agriculture and is funded by the federal government and the various states, often with support from local commodity groups. The plant research in these institutions is primarily geared towards improving field crops and horticultural and forest species of major economic importance to a state's agriculture. For example, the Oklahoma State University, an Oklahoma land grant university, conducts research on wheat, the most important crop in the state. A fee is levied on produce presented for sale at the elevator by producers and used to support agricultural research pertaining to wheat.

In addition to its in-house research unit, the Agricultural Research Service (ARS), the USDA often has scientists attached to land grant institutions to conduct research of benefit to a specific state as well as the general region. For example, the Grazinglands Research Laboratory at El Reno, Oklahoma, is engaged in forage research for the benefit of the Great Plains. Research output from land grant programs and the USDA is often public domain and often accessible to the public. However, just like the private sector, inventions may be protected by obtaining plant variety protection or a patent.

The UK experience[1]

The equivalent of a land grant system does not operate in the United Kingdom but, up to the 1980s, there were a number of public sector breeding programs at research institutes such as the Plant Breeding Institute (PBI) (now part of the John Innes Centre), Scottish Crop Research Institute (SCRI), Welsh Plant Breeding Station (now the Institute of Grassland and Environmental Research (IGER)) and National Vegetable Research Station (now Horticultural Research International (HRI)), with the products being marketed through the National Seed Development Organisation (NSDO). In addition, there were several commercial breeding programs producing successful finished cultivars, especially for the major crops. Following a review of "Near Market Research", the plant breeding program at the PBI and the whole portfolio of the NSDO were sold to Unilever and traded under the brand PBI Cambridge, later to become PBI Seeds. The review effectively curtailed the breeding activities in the public sector, especially of the major crops. Plant breeding in the public sector did continue at the IGER, HRI and SCRI but was reliant on funding from the private sector for a substantial part of the program. Two recent reviews of crop science research in the United Kingdom have highlighted the poor connection between much public sector research and the needs of the plant breeding and end-user communities. The need for public good plant breeding was recognized in the Biotechnology and Biological Sciences Research Council (BBSRC) Crop Science Review to translate fundamental research into deliverables for the end-user and is likely to stimulate pre-breeding activity at the very least in the public sector.

[1] The information regarding the United Kingdom experience is through personal communication with W.T.B. Thomas of the Scottish Crop Research Institute, Invergowrie, UK.

Crop research and development in European Community (EC) countries

Unlike the United States, the private sector is responsible for cultivar development of established crops, while the public sector focuses on research. However, in the case of new crops where risk investment is high, the public sector (governmental institutes) engages in both research and cultivar development. Several research and development arrangements occur in Europe.

- Agro-industrial programs. These programs involve partnership between two or more countries and may include private sector in some cases. Their activities include development of new potential crops (*Cuphea*, jojoba, castor bean, lupines, Jerusalem artichoke), industrial processing, primary production, transformations and utilization of biological feed stocks.
- Bilateral programs. These are informal partnerships between countries that may include germplasm and information exchange.
- National program. Universities and agricultural research institutes work on new crops.
- Industrial programs. These are conducted by the private sector and may include the search for new crops of pharmaceutical value, as well as bioactive compounds. Sometimes, public sector institutes may be engaged.

International plant breeding

There are other private sector efforts that are supported by foundations and world institutions, such as the Food and Agriculture Organization (FAO), Ford Foundation, and Rockefeller Foundation. These entities tend to address issues of global importance and also support the improvement of the so-called "orphaned crops" (crops that are of importance to developing countries, but not of sufficient economic value to attract investment by multinational corporations). Developing countries vary in their capabilities for modern plant breeding research. Some countries, such as China, India, Brazil, and South Africa, have advanced plant breeding research programs. Other countries have national research stations that devote efforts to the breeding of major national crops or plants, such as the Crops Research Institute in Ghana, where significant efforts have led to the country being a leading adopter of quality protein maize (QPM) in the world.

1.9.3 Public sector versus private sector breeding

Public sector breeding is disadvantaged in an increasingly privatized world. The issues of intellectual property protection, globalization and the constraints on public budgets in both developed and developing economies are responsible for the shift in the balance of plant breeding undertakings from the public to the private sector. This shift in balance has occurred over a period and differs from one country to another, as well as one crop to another. The shift is driven primarily by economic factors. For example, corn breeding in developed economies is dominated by the private sector. However, the trends in wheat breeding are variable in different parts of the world and even within regions in the same country. Public sector plant breeding focuses on problems that are of great social concern, even though they may not be of tremendous economic value (having poor market structure), whereas private sector breeding focuses on problems of high economic return. Public sector breeders can afford to tackle long term research while the private sector, for economic reasons, prefers to have quicker returns on investment. Public sector breeders also engage in minor crops in addition to the principal crops of importance to various states (in the case of the land grant system of the United States). A great contribution of public sector research is the training of plant breeders who work in both the public and private sectors. Also, the public sector is primarily responsible for germplasm conservation and preservation. Hence, private sector breeding benefits tremendously from public sector efforts.

It has been suggested by some that whereas scientific advances and cost of research are relevant factors in the public sector breeding programs, plant breeding investment decisions are not usually significantly directly impacted by the market structure and the organization of the seed industry.

A major way in which private and public breeding efforts differ is on the returns to research. Public sector breeders are primarily not profit oriented and can afford to exchange and share some of their inventions more freely. However, it must be pointed out that access to some public germplasm and technologies is now highly restricted, requiring significant protocol and fees to be paid for their use. The public sector plays a critical role in important activities such as the education and training of plant breeders, development of new methods of breeding, and germplasm preservation and enhancement. These activities are generally long term and less profitable, at least in the short run, and hence less attractive to the private sector.

1.10 Duration and cost of plant breeding programs

It is estimated that it takes about 7–12 years (or even longer) to complete (cultivar release) a breeding program for annual cultivars such as corn, wheat, and soybeans, and much longer for tree crops. The use of molecular techniques to facilitate the selection process may reduce the time for plant breeding in some cases. The use of tissue culture can reduce the length of breeding programs of perennial species. Nonetheless, the development of new cultivars may cost from hundreds of thousands of dollars to even several million dollars. The cost of cultivar development can be much higher if proprietary material is involved. Genetically engineered parental stock attracts a steep fee to use because of the costs involved in its creation. The cost of breeding also depends on where and by whom the activity is being conducted. Because of high overheads, similar products can be produced by breeders in developed and developing economies, but for dramatically higher cost in the former. Cheaper labor in developing countries can allow breeders to produce hybrids of some self-pollinated species less expensively, because they can afford to pay for hand pollination (e.g., cotton in India).

1.11 The 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, farmlands 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:

- **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. The technology has been around for over a decade. Strategies are being perfected for the use of plants to generate pharmaceutical antibodies, engineering antibody-mediated pathogen resistance, and altering plant phenotype 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.
- **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. Genomics and bioinformatics will continue to be influential in the approach of researchers to crop improvement. Marker assisted selection (MAS) will be important in plant breeding in the twenty-first century.
- **Training of plant breeders.** As discussed elsewhere in the book, plant breeding programs have experienced a slight decline in the number of graduates entering the field in the 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, then provide them the needed plant breeding skills on the job.
- **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 is likely to continue in the future. Publically-supported breeding efforts will decline in favor of for-profit programs.
- **Yield gains of crops.** With the dwindling of arable land and the increasing 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 yield 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.

- **The biotechnology debate.** It is often said that these modern technologies for plant genetic manipulation benefit the developing countries the most because they are in dire need of food, both in quantity and nutritional value. On the other hand, the intellectual property that covers those 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 these poorer developing nations will continue, to enable them 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 Rice varieties were the first products of the experiments leading to the Green Revolution.
2 Rice is high in pro-vitamin A.
3 The IR8 was the rice variety released as part of the Green Revolution.
4 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 Green Revolution.
2 Define plant breeding.
3 Give three common 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 discuss in the following questions in detail.

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.
7 Discuss the concept of breeder's eye.
8 Discuss the general steps in a plant breeding program.
9 Discuss the qualifications of a plant breeder.
10 Distinguish between public sector and private sector plant breeding.
11 Discuss the molecular and classical plant breeding approaches as complementary approaches in modern plant breeding.