CHAPTER

Plant breeding: past, present, and future perspectives

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Abstract

This chapter focuses on the past, present, and future of plant breeding particularly geared toward cultivar development. Plant breeders have made tremendous progress in the genetic enhancement of yield, adaptation traits, disease−pest resistance, abiotic stress tolerance, and nutritional and/or end-use quality, increasing crop production and the productivity (yield per unit area) of major crops. With the increasing needs of human population and an ever-increasing climatic variability, plant breeding becomes more important than ever to respond to production challenges to ensure a stable food, feed, and fiber supply. The recent research advances in the areas of biotechnology, genomics, and phenomics provide sophisticated tools to plant breeders to build improved cultivars. Major topics covered in this chapter include crop domestication, pre-Mendelian and Mendelian plant breeding, and plant breeding in the 20th and 21st centuries, which include details on green revolution, genetically modified crops, molecular marker tools, image-based phenotyping, machine learning methods, relationship between private and public sector plant breeding organization, and future plant breeding efforts.

Plant breeding began with the domestication of wild plants and the cultivation of plants, which were useful to man. The process of selecting plant types that provided a dependable source of food, feed, fiber, oil, and other useful products was a part of domestication; therefore, selection became the first method of plant breeding. Selection depends on practitioner's knowledge of plant itself and its response to its environment. The experience plays an important role that is why plant breeding was considered as an art rather than science; and selection continued for thousands of years until human could learn about the structure and function of male and female flowers and their role in the formation of seed. Hybridization was used in certain species to develop superior strains without the knowledge of inheritance of traits (i.e., genetics). The discoveries of cell and their organelles, Mendel's laws and their rediscovery, their application in plant breeding, and infusion of learnings from various scientific disciplines started to make plant breeding more as a science and less of an art discipline.

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Plant breeding deals with the inheritance of qualitative and quantitative traits and includes the genetic improvement in existing genotypes for specific trait(s), and the creation of altogether new genotype with new gene combination called recombinant. Present day plant breeding also involves integration of alien gene(s) from plant kingdom or beyond. Through plant breeding, plants have been improved for their productivity, quality traits (physical and chemical), and also for various other desirable traits, such as resistance to environmental stresses and harmful parasite and for their suitability to mechanical harvesting. Plant breeding is also referred to as plant/crop improvement. In view of these considerations, plant breeders need to be trained not only in genetics (population, quantitative, and Mendelian) but also in related disciplines, including agronomy, biotechnology, entomology, food science, molecular genetics, pathology, physiology, and soil science and many more. A plant breeder is required to have general understanding of the crop(s) including cultivars being grown by the farmers and their problems in different cropping systems and niches, needs of consumers, and industries. Therefore, it is imperative that a plant breeder has a general understanding and knowledge of related disciplines such as crop physiology, crop protection, crop husbandry, biochemistry, and statistics including field plot techniques and analysis. With the advent on modern genomic technologies, phenomics, and mechanization/computerization, they also need to be aware or moderately experienced in computer programing.

In this chapter, historical development of plant breeding, role of plant breeding in the welfare of mankind, its present scenario, and future perspectives are described in brief.

Primitive agriculture and crop domestication

Archeological evidence suggests that angiosperms (higher plants, also called flowering plants) appeared at the end of Mesolithic age and human beings invented agriculture during Neolithic age. They used stone implements for cultivation that was the beginning of primitive agriculture, which was a switch off from the lifestyle of hunting and gathering. Until the Neolithic period, humans devoted a great deal of time and energy in search of food that was largely through hunting and gathering of animals and plants. This lifestyle changed in due course when they started domesticating plant species some 10,000 years ago. It was a gradual and slow process of change where plant species generated enormous variability through mutations, cross-pollination, and recombination (through natural hybridization). Of these variations, variations only favorable (i.e., advantageous) for adaptation to the environmental conditions were primarily selected by nature and others not fit for survival were lost. It is believed that the beginning of agriculture and plant domestication of our present-day plant species occurred thousands of years ago at different times and places. These places were geographically isolated and inhabited by different societies around the world, and were called as centers of origin (and later named centers of diversity). The currently cultivated crop species were domesticated from wild types at these centers, and from these centers domesticated plants first spread. Probably the first development in plant breeding occurred with the domestication of wild plants such as wheat, barley, and lentils around 13,000−10,000 years ago. It is suggested that perhaps the first successful selections were made in the Fertile Crescent in Eurasia between 9000 and 7000 BCE along the Tigris and Euphrates rivers in the present day Iraq extending into Iran and Southeast Turkey on the north, and south into Lebanon, Israel, and Southern highlands. This area shows a rich diversity of cereals and pulses.

The wild species progenitors have traits for adaptations, for example, the wild species of cereals were tall, branched, or bushy, and in case of wild species of legumes the plants were trailing type. In general, the wild species produced small seeds with undesirable appearance and hard seed coat. The spikes of cereals and pods of legumes were prone to shattering. In nature, these traits were helpful for seed dispersal and perpetuation from year to year. Other traits that were altered during domestication included size and shape of foliage, tubers, berries, fruits, and grains that increased yield, give better nutritional ability, and other desirable traits. Molecular analysis has revealed that key factors that distinguished a domesticated plant from its wild type are often in the genes that encode transcription factors, proteins that regulate the expression of many other genes (Doebley et al., 2006). Mutation in the genes coding for protein of certain biosynthetic pathways give rise to difference in nutrient composition among varieties of the same crop. These include mutations in genes that created sweet corn varieties, lower lignin for improved digestibility for livestock, and improved fatty acid profile in oilseed crops.

Of the thousands of plant species, only few plant species were domesticated for food, fiber, oil, and other human use. Of about 250,000−300,000 plant species, 10,000−12,000 (4% of total plant species) are edible but less than 200 are used. Furthermore, rice, wheat, and maize contribute ~60% of the calories and protein consumed by humans from plant sources (FAO 1999, 2004), and about 30 crop species provide calories and nutrients that humans need every day.

Pre-Mendelian plant breeding

The Assyrians and Babylonians in ancient times recognized that date palms were of two types, male and female. As early as 700 BCE reportedly people in these civilizations hand pollinated date palms, which was one of the oldest domesticated fruit trees. Selection of superior seed was mentioned during Roman times. First real description of sex and plant hybridization was made by Rudolph Camerer (also known as Camerarius) (1665−1721) at the University of Tübingen in Germany. He conducted experiments on mulberry, castor bean, spinach, and maize and showed that pollen produced on male flowers was indispensable to fertilization and seed development on female plants. He, however, did not work with plants of both sex organs in a single flower. Botanist Richard Bradley (1688–1732) used controlled experiments to observe that pollen had a role in fertilization. He made this conclusion after observing that if he removed pollen producing stamen of the flower, in isolation no viable seed was produced. He also reported controlled (and not random) cross-fertilization as a path of fruit improvement. It has been reported that in the 17th century in China, the Emperor Khang Hi (1662–1723) selected an early maturing rice plant from his garden, which was multiplied and cultivated widely because of desirable quality and was named Imperial Rice.

Thomas Fairchild an Englishman in 1717 produced an interspecific cross between Sweet William (*Dianthus barbatus* L.) as female and Carnation (*Dianthus caryophyllus*) as pollen parent and the product was known as Fairchild's Sweet William (also called Fairchild's Mule), which was sterile. In 1716, an American, Cotton Mather observed that ears from yellow corn grown next to blue or red corn had blue or red kernels in them, suggesting the occurrence of natural cross-pollination. Jean-Baptiste van Mons (1765–1842) observed that seed of the oldest trees (with good fruits) generally produce inferior progeny, and seed of the young trees (even with bad fruit) produce superior progeny (with good fruits). Van Mons developed a lot of varieties in fruit trees (particularly pears) by sowing seed from younger trees (with good fruits), selecting the best progenies (seedlings) to obtain new seed (fruits), and repeating the process to develop superior varieties (and after four to five generations, nearly all progenies were considered superior). However, the decline in older varieties is probably attributed to diseases and other factors, and not all hybridizations were planned. Thomas Knight (1759–1838) is mostly known for his work on phototropism and geotropism, and on fruit trees, strawberry, and pea breeding. He made controlled crosses (in late 1700s) and kept record of progeny performance to develop varieties. However, these efforts were led by individuals. Philippe-Victoire Levêque de Vilmorin and his wife revived the plant and seed company of her parents Claude Geoffroy and Pierre Andrieux, which later became the Vilmorin-Andrieux seed company in the mid-18th century. The Vilmorin breeding efforts in France included work on individual plant selection based on progeny test (was used for improving sugar content in sugar beet), which was called Vilmorin Isolation Principle (however, this method was not effective in sugar beet, a cross-pollinated crop).

The Swedish Botanist Carlous Linnaeus (1753) published Species Plantarum and established the binomial nomenclature, which consisted of generic name and a species name, for example, *Zea mays* for maize. This work helped in the understanding of the plant species as the system used number and arrangement of reproductive organs (stamens and pistils) as the critical characteristics for nomenclature. The first systematic investigations into hybridization were conducted in many plant species (54 species belonging to 13 genera) by Joseph Koelreuter (between 1760 and 1766) in Germany, who promoted theory of fertilization and artificial hybridization. Most of the crosses resulted in sterile progenies, which suggested that hybridization in general is possible between closely related plants. He produced fertile hybrid in *Nicotiana* (e.g., *Nicotiana paniculata* and *N. rustica*) and demonstrated that hybrid progeny received traits from both parents and were intermediate in most traits. He also reported varying degrees of sterility from his experiment involving interspecific observed luxuriance, and postulated commercial potential of hybrid vigor. Christin Konrad Sprengel (1750–1816) identified self- and cross-fertilized plants. This provided better understanding about floral morphology and mode of pollination, and that the function of flowers was to attract insects for pollination.

Thomas Andrew Knight (1759–1838) in late 18th and early 19th century effectively selected superior cultivars of fruits and vegetables through crossing to improve useful food plants for better quality traits. Superior progenies of a cross were identified and were asexually propagated, thereby overcoming subsequent segregation and reselection. Patrick Shirreff, a Scotsman, began his work on wheat and oat crops in 1819. He practiced selection in these crops and developed superior pure line cultivars. For the first time he evaluated his selections along with other in plots, which were sampled and data were recorded on height, maturity, and other agronomic traits. Henry Zimmerman in 1837 in Maryland selected pure line cultivar in wheat after noticing three ears of singular appearance near the edge of his wheat fields. These were grown for seed increase and after 6 years, seed was sold to the public as "Zimmerman" wheat (white kernel wheat). John Le Coutier (1836) published his results on selection in wheat and reported that progenies from single grain or ear were more uniform and pure. David Fife, a farmer from Ontario, Canada, made a selection named Red Fife in 1842, which came from a seed lot by Fife from Poland (via Scotland) in 1841. From the winter wheat lot, only one plant produced spikes as the rest did not produce spikes because they were spring seeded and therefore, did not have a winter cold treatment for vernalization. Fife harvested the seed from this single spring wheat plant and increased them to develop the cultivar Red Fife, which possessed excellent bread making qualities and it credited to have ushered in an exponential wheat growth in Canada. It was the first truly hard red spring wheat in North America that made substantial contribution to agriculture as it became the predominant parent in the development of improved cultivars including Marquis spring wheat, which compared with Red Fife was short statured, less prone to shattering, and higher yielding with similar bread making qualities.

In middle of the 19th century, Hallett in England carried out his work in what is known as "head-row method" and he believed that selection within a pure line can affect improvement if practiced over multiple generations. He practiced single plant selections in wheat, oat, and barley and developed several commercial varieties. William James Farrer (1845–1906), a famous Australian wheat breeder, is best recognized for his early maturing wheat variety Federation for its general resistance to rusts, grain quality, and adaptation traits. He is credited for visualizing ideotype of wheat including shorter stature, stiff straw, and narrow leaves.

It should be mentioned that much of his work was conducted prior to the universal understanding of principles of genetics and helped establish a flourishing wheat breeding industry in Australia. Luther Burbank (1849−1926) made outstanding contributions to crop breeding, and probably he can be considered the most successful plant breeder. He was responsible for the development of 800 strains of asexually propagated plant species including Burbank and Russet Burbank potatoes, "spineless" cactus, walnuts, berries, ornamentals, flowers, vegetables, stoneless plum and semi- and free-stone plums, plumcot (cross between plum and apricot), and many more crop plants. Russet Burbank potato cultivar became the world's predominant potato in the food processing industry.

It may be emphasized that prior to 1900 much of the plant breeding was practiced not by the trained geneticists and plant breeders but by farmers, amateurs, and non-scientist who selected seed or clone from preferred plant types of land races or populations for subsequent sowing. This period was also devoted to the understanding of the floral structure and function of both self- and cross-fertilized species. Some of the workers also made successful crosses among closely related species and less closely related species. The crosses were fertile between closely related species, whereas less related species produced sterile F_1 hybrids. However, the mechanism of segregation and genetic principles was not universally understood (or mainstream).

Mendelian plant breeding

During the 18th century, hybridizations were made by several researchers and interesting results were obtained. New varieties were produced from such crosses; however, mechanism of fertilization, that is, the development of pollen tube and its approach to the ovule was discovered around 1833. Robert Brown an English botanist did considerable work on this problem. The cell theory first put forward convincingly in 1839 by German microscopists Schleiden and Schwann proposed that all plants and animals are constructed from small fundamental units called cells. The cell contains nucleus and cell organelles, which are surrounded by the cell membrane. The discovery of strand-like structure, that is, chromosomes by C.W. Nageli in 1842, was followed by the discoveries of the cell divisions (mitosis and meiosis) by work of several researchers (including Nageli and Robert Remak). This helped in the understanding that the cells arise from other cells by the process of cell divisions and the traits are transmitted from generation after generation.

During this period, attempts were being made to use hybridization to develop superior cultivars both in cross- and self-fertilized crop species. Gartner in Germany made extensive crosses involving some 700 species and obtained 250 hybrids, and this work was published in 1849. In 1847−48, American farmer Robert Reid in Illinois crossed a semigourd seed dent with little yellow to create Reid Yellow Dent. Robert Reid and his son James Reid improved the variety for ear selection, higher kernel rows, brighter yellow color, etc. Reid yellow dent is reported to be in the background of about half of modern maize hybrids in the United States. However, after native Americans, the first variety development records suggest that Noyes Darling (1844) developed a white seeded sweet maize variety called Indian Corn using systematic breeding approaches (Singleton WR, 1944). For hybridization of maize, detasseling of female plants was done to allow male plants (yellow corn) to pollinate female plants (sweet corn). The earliest recorded attempt to develop barley cultivars using hybridization was made by F.H. Horsford in 1879 in the United States.

The Scientific foundation for evolution was laid during the second half of 19th century through the writings of an English scientist Charles Darwin. He described the theory of evolution in his book "Origin of Species by Natural Selection." His theory was based on few important features: (1) overproduction of offspring and consequent struggle for existence, and that there are some forms that will be more successful at surviving and reproducing than other forms in a given environment, (2) variations and their inheritance, such that with any population there will be variation in morphology, physiology, etc., among individuals, (3) elimination of unfavorable variations (i.e., survival of the fittest), and (4) offspring resemble their parents more than they resemble unrelated individuals. He proposed that dissimilarities seen in cultivated plants from their wild relatives were due to selection pressures imposed by early man. Darwin's theory formed consciously or subconsciously approaches for crop improvement in the late 1800s along with Mendel's law of inheritance.

Gregor Johann Mendel (1822−84), an Austrian monk, formulated the fundamental laws of inheritance (i.e., the law of segregation and the law of independent assortment). The Mendelian laws of genetics form the basis of classical genetics. Mendel performed his scientific investigations for 8 years (1857−1965) in the monastery garden at Brunn (Austria) on hybridization of plants, particularly garden peas, a self-fertilized plant. He presented results of his experiments before the Natural History Society of Brunn in 1865. While describing the results Mendel used the term "factors" for the unit of inheritance, which were later on called "genes" by Johannsen. The proceedings of the society were published in the *Transactions of the Brunn Natural History Society* but had limited circulation. Therefore, the work of Mendel remained unnoticed for 35 years until three distinguished botanists DeVries in Holland, Tschermak in Austria, and Correns in Germany working independently rediscovered the Mendel's laws in 1900, which provoked a tremendous scientific interest in genetics and had great influence on the development of plant breeding.

Plant breeding in the 20th and 21st centuries

The rediscovery of Mendel's laws opened up a new era in plant breeding. Before these principles were understood, plant breeding was more an art. However, Mendelian principles accelerated the exploitation of naturally occurring genetic variability and in the generation and manipulation of combination of new variability, and as a result, plant breeding became more of science and less an art.

Johannsen (1903), the Danish botanist, developed pure line theory of selection in Princess bean (*Phaseolus vulgaris* L.) (pure line is a progeny of a single self-fertilizing individual). Nilsson-Ehle (1909) proposed the existence of polymeric (multiple) factors for inheritance of seed coat color in wheat. He gave scientific background to transgressive breeding, fully explaining the advantage of recombination breeding. Wilhelm Rimpau (1842–1903) was one of the earliest to develop a partially fertile hybrid from wheat/rye cross and this work led to the later development of triticale crop species. East (1908) working at the Connecticut Experiment Station, in the United States, published his work on inbreeding in maize. Shull (1908, 1909) at Cold Spring Harbor conducted extensive research to develop homozygous lines and the best two lines were used to develop hybrids in maize. The discoveries of East and Shull in maize were instrumental for the wide application of hybrid vigor in other crop plants including field crops, vegetables, and horticultural plants. Jones (1918) suggested the production of double cross hybrids in maize using four inbreds, and the commercial seed was produced on high-yielding single cross parents, as at that time single cross commercial hybrid proposed by Shull was considered infeasible for seed quantity production.

Nikolai I. Vavilov (1887–1943) is recognized as the foremost plant geographer, botanist, and geneticist of contemporary times. He was ahead of his time; as he was a pioneer in genetic resource management. After several years of investigations, he proposed now the familiar eight centers of origin. He anticipated genetic erosion and therefore, he organized and took part in more than 100 germplasm collecting missions in the major agricultural areas of the world and concluded that the greatest species variation occurred in certain restricted areas (centers of diversity), which he believed identified the centers of origin of those species. He insisted on a systematic classification, evaluation, and utilization of vast assembled collections. He is credited for creating one of the world's largest seed repository with over 250,000 accessions. Vavilov also proposed law of homologous series in hereditary variation.

Muller (1927) for the first time demonstrated the ability of X-rays to induce genetic variation in fruit fly (*Drosophila melanogaster*). This work was used in crop plants (barley) by Stadler (1928). The discovery of X-rays as mutagen and its use to induce variation had initiated a new field, that is, induced mutagenesis, which was used as an important tool in basic studies (i.e., locating genes on chromosomes, studying gene structure, expression, and regulation, and for exploring genomes). Plant Breeders across the globe started to investigate the use of radiation-induced mutations. More than 2252 mutant varieties have been released (Maluszynski et al., 2000). Of these 1585 were crop varieties released as direct mutant, and 667 were derived through crosses with induced mutants; however, more varieties have been developed since the publication. Mutation breeding approach has been used in sexually propagated crops with small flowers which are difficult to cross and in asexually vegetatively propagated crops. In general, mutation breeding approach has been to improve the well-adapted plant varieties by altering one or few major traits.

During the 20th century, plant breeders and geneticists were trained in the colleges and universities and several experiment stations were established across the world. Most of plant breeding was directed toward collection of the indigenous variability and introductions of exotic materials. The improved cultivars of self-pollinated crops were developed using pure line selection. The plant breeders developed specialized techniques of hybridization and used diverse lines to cross and generate segregating generations to select superior segregants. The mass selection and its modifications were used to improve the cultivars of cross-pollinated crops which were largely populations, but hybrids were rapidly gaining popularity in some regions (e.g., the United States). The inbred lines were produced through artificial selfing and superior inbred lines were used to develop hybrids. Clonal selection was used to develop superior clones in vegetatively propagated crops. The field plot techniques were developed for testing the improved genotypes. The use of field designs and statistical analysis of agronomic and other traits data added precision in varietal evaluation. To develop varieties with stable performance for adoption in wider areas, multilocation testing was used. The data were recorded not only for agronomic traits but also for resistance to biotic and abiotic stresses. Genotypes with (significantly) higher yield when compared with previously cultivated check cultivar were promoted for further testing and commercialization. The line(s) which possessed resistance to one or two major stresses of the area/region were released for commercial cultivation. This period also witnessed the development of network for seed multiplications of cultivars/hybrids, and as a result several private companies came into existence.

Green revolution

Since the time immemorial, the scarcity of food has always been a problem for the human civilization. Food shortages have caused several famines; some of these are well documented (e.g., the Irish famine of 1840s, and Bengal famine of 1943 in India). Moreover, the human population in certain regions of the world grew at a much faster rate and food production increased at a slower rate, leading to insufficient food supply necessitating steps to be taken at the National and International levels. In view of the food shortages, serious efforts were made in the 20th century to achieve yield increases in major food crops including cereals, such as maize, wheat, rice, sorghum, and pearl millet. The remarkable events were the shift toward single-cross maize hybrids, use of cytoplasmic genetic male sterility in the production of hybrid varieties in maize, sorghum, and pearl millet, and semidwarf varieties of rice and wheat. The genesis of semidwarf wheat and rice and their cultivation were responsible in quantum jump in yield gains of these crops in several countries and was termed "Green Revolution."

In the middle of 1920s H.A. Wallace founded pioneer Hi-Bred Seed Company and produced hybrid corn; however, due to the disastrous economic depression of 1930s, the use of hybrids did not really take off until the early 1940s. By the mid-1950s, double cross hybrid dominated US maize production and open-pollinated varieties had virtually disappeared. Later on in the United States, the double cross hybrids were replaced by single cross hybrids further increasing yields in 1960s. H.A. Wallace, who himself was a breeder, became Secretary of Agriculture and the US Vice-President under Roosevelt. He interacted with J.A. Ferrell from the Rockefeller foundation to promote agriculture initiative in Mexico and launched a program of crop breeding in Mexico. The Mexican Government in collaboration with the Rockefeller foundation launched a project in 1943, to set up the Mexican Agriculture Program, which is credited with ushering in the green revolution. N.E. Borlaug, a plant pathologist, joined this project in 1944 where he along with his team of dedicated scientists developed higher yielding stem rust-resistant varieties of wheat and appropriate practices including fertilizer, irrigation, tillage, disease, and pest management for optimizing the yield potential of these varieties. The concept of shuttle breeding was also initiated at this time (1945) to reduce the time to develop varieties; and shorter statured varieties responsive to irrigation and fertilizers began to be developed. In view of encouraging results from this program, the Rockefeller Foundation decided to establish an independent institute, which was named, International Maize and Wheat Improvement Centre (CIMMYT) headquarter in Mexico. CIMMYT was created (1966) by merging several regional and country research programs initiated by the Rockefeller Foundation with a focus on international agricultural research and programs tackling global food security. Rockefeller Foundation and Ford Foundation joined hands with the Philippines government to establish the International Rice Research Institute (IRRI) near Manila (Los Banos) in 1962. IRRI focused on research and breeding of rice, which was staple food across the world, to mirror the wheat crops' transformation and adoption.

During the 1960s, efforts were being made to introduce green revolution programs in developing countries including, India, Pakistan, Philippines, and Indonesia, through partnerships between federal governments and the international programs of IRRI and CIMMYT. The semidwarf varieties of wheat developed at CIMMYT by Borlaug and the wheat breeders, and rice varieties developed by H.M. Beachell and the rice breeders at IRRI spread in developing nations and became very popular in 1960−70s in the wheat and rice growing reasons in several countries including India and Pakistan. The new varieties, along with improved management practices revolutionized the wheat and rice production in these countries and saved millions of people from starvation. Borlaug was awarded the Nobel Peace Prize in 1970 for this work.

The traditional cultivars of wheat and rice grown prior to Green Revolution were tall, leafy with weak stems that were prone to lodging; and non-responsive to high yield conditions and environments. Such varieties had a harvest index of 0.3. Contrary to this, the semidwarf varieties of wheat and rice had a harvest index of 0.5 that gave at least two to three times higher yield than the local varieties. *Norin 10* variety from Japan was the source of semidwarf wheat that channeled the wheat green revolution. Two US varieties, Fultz and Turkey red, are in the lineage of Norin 10. Glassy Fultz was developed using pedigree method and was crossed as a male with Daruma as a female (donor for semidwarf trait, contained recessive dwarfing genes *rht1* and *rht2*) to create Fultz-Daruma. In 1924, Fultz-Daruma was crossed with Turkey Red (as female), and F_3 selection named Tohoku No. 34 was named Norin 10. Norin 10 was released in 1935. Norin 10 and other similar Japanese lines showed short stiff straw with higher tillering capacity. S.C. Salmon brought Norin 10 and 15 other varieties from Japan to the United States and was used in breeding of the semidwarf winter wheat variety Gaines by Orville Vogel of USDA and released in 1961. Gaines was developed from a multiple parent cross. The original cross made in 1949 was Norin 10 $\times$ Brevor, and selection from this cross was crossed with a selection from a cross of Orfred and sister selection of Brevor. The selection from this cross was crossed with Burt in 1952.

The semidwarf winter wheat cultivar Gaines was used by Borlaug in hybridization with Mexican strains to develop semidwarf spring wheat cultivars. He used shuttle breeding, where in different generations were grown at two diverse environments, that is, sites which were located at different latitudes with changing day length and altitudes by 2600 m and were different in terms of soil temperature, rainfall, and photoperiod. In summer, wheat crop was grown at high altitude near Mexico City, while in winter season they used the Yaqui Valley of northern Mexico (under irrigation plots, Sonoran Desert). Only the varieties that withstood the rigors of both environments were advanced in the breeding program. At CIMMYT, cultivars Hope (a stem rust-resistant wheat from the United States) and Frontana (a leaf-resistant Brazilian cultivar) were used to transfer their durable resistance (*Sr2* gene complex from Hope, and *Lr34* gene complex from Frontana). The improved varieties developed using the above methodology along with appropriate agronomic packages resulted in fourfold increased productivity in Mexico. Some of these varieties were introduced into other parts of the world, including India, Pakistan, and Turkey in 1966 with spectacular results.

Similar approach was used in rice at IRRI, and semidwarf varieties were released in mid-1960s to farmers in the Philippines. Of these, IR8 was most successful; it was semidwarf, early maturing, non-photosensitive, and nitrogen responsive with high yield potential. Due to its earlier maturity, it was suitable for double cropping in certain rice growing regions. IR8 was developed from a cross of Indonesian variety Peta (from a cross between Indian variety Latisail and the Chinese variety Cina) as female and a semidwarf Taiwan cultivar Dee-Geo-Woo-Gen (DGWG) was used as male. DGWG possessed a single recessive semidwarf gene *sd1*. IR8 had stiff straw, was resistant to lodging and photoperiod insensitive making it widely adapted. IR8 and several other varieties with IR series were introduced in other rice growing countries of Southeast Asia where these varieties gave higher and stable yields, generating a name of miracle rice. The higher yields were obtained due to their responsiveness to higher doses of fertilizers and other inputs in contrast to the local varieties that were prone to lodging.

The green revolution was successful in increasing the world production of cereals and thereby provided availability of food. However, the achievements of green revolution have been criticized by some that it has benefited the rich and large farmers in areas where irrigation facilities were available, and the technology was not environment friendly as excessive use of agrochemicals is responsible for soil degradation.

The next revolution that has ushered in increased crop productivity relates to biotechnology innovations. Biotechnology and molecular tools have been used to boost agriculture production, and these include genetically modified (GM) crops and marker-enabled breeding to develop higher yielding varieties with desirable traits.

Genetically modified crops

The GM or transgenic plant is one that contains a gene or genes which have been introduced artificially into the plant's genetic make-up using a set of biotechnology techniques collectively known as recombinant DNA (rDNA) technology. Transgene(s) are transferred using either particle bombardment or plasmid-mediated transformation. Once stably transformed, the transgene(s) is inherited along with the rest of the plant genes. The offspring (plants) carrying transgene(s) are also transgenic plants. Major examples of crops grown with Genetically Modified Organism (GMO) technology and grown on farmer fields, include insect-resistant (IR) "*Bt*" cotton, maize, and canola; herbicide-resistant soybean, cotton, and maize; viral disease-resistant papaya, etc.

The GM revolution started with discoveries in the 1980s by M. Montagu, J. Schell, and M. Chilton who discovered a natural gene transfer mechanism between *Agrobacterium tumefaciens* and plants. The tumor causing genes of *Agrobacterium* could be replaced by other genes not present endogenously in the crop species to create new crop trait package. The GM cultivars were developed in 1990s and were first commercialized in the United States in 1996. The two major types of GM crops in the US row crops are herbicide tolerant (HT) and IR.

The HT traits include tolerance against herbicides, such as glyphosate, glufosinate, and dicamba. These expand farmer's ability to control weed in their field more effectively. As per the ERS-USDA (2019), the HT soybean acres in the United States have expanded from 17% in 1997 to 94% in 2014, and in 2019 it has grown to 98%. Similarly GM cotton with HT trait has also grown from 10% in 1997 to 98% in 2019. In 2019 maize HT trait crops were grown in 92% of the total acres. The IR traits include primarily genes from the soil bacterium *Bacillus thuringiensis* "*Bt*." The bacteria produces crystalline protein called Cry protein that has a high target specificity to control insect–pest (Cry toxins only impact insects of specific taxonomic order and are shown to be safe to mammals). Some of the destructive insects controlled by the *Bt* toxin are European corn borer, rootworm, corn earworm, and bollworm. In the United States, IR *Bt* corn acres have grown from 8% in 1997 to 83% in 2019. The IR *Bt* crops have grown from 15% in 1997 to 92% in 2019 (ERS-USDA, 2019). The increase in crop acre percentage is likely due to the newer IR stacked maize hybrids that have IR traits that provide protection against both corn borer and corn rootworm (additionally corn earworm and fall armyworm); while the earlier hybrids only provided protection against the European corn borer). The Bt technology in cotton varieties has upgraded from a single-gene trait to multigene trait packages. The first-generation *Bt* cotton had a single *Bt* gene, the second generation had two *Bt* genes (producing two toxin proteins), and more recently to a third generation has a three *Bt* gene package combining crystal (Cry) and vegetative insecticidal proteins (Vip). *Bt* cotton can control bollworm, tobacco budworm, pink bollworm, and (Beet and Fall) armyworm infestations.

The global crop hectarage of GM crops continued to grow from 1.7 m ha in 1996 to 191.7 m ha in 2018. These crops were grown by 17 million farmers in 26 countries (ISAAA, 2018). The adoption rate of GM crops speaks of sustainability and benefits it delivers to the growers and consumers. In 2017, the United States had maximum area under GM crops (75 m ha), followed by Brazil (51.3 m ha), Argentina (23.9 m ha), Canada (12.7 m ha), and India (11.6 m ha). The area in India of GM crop is only from cotton. Soybean are the most widely grown GM crop worldwide, with 50% (95.9 m ha) of the global biotech crops and 78% of the total global soybean production (ISAAA, 2018). In maize, 31% of the global maize production is with GM crops.

The major GM crops are soybean, maize, cotton, and canola, while the other crops with GM grown varieties include alfalfa, papaya, eggplant, potato, safflower, apple, and sugarcane (ISAAA, 2018). Not all GM varieties are developed by transgene DNA sequences. For example, Arctic apple was created by introducing antipolyphenol oxidase (anti-PPO) RNA [using RNA interference (RNAi) technology]. The RNAi is used to lower PPO levels in apple by introducing RNA sequences that cause the degradation of PPO RNA, therefore, no PPO enzymes are produced leading to non-browning apples when cut.

As per ISAAA (2016), since 1996, in the United States 195 single trait events in 20 crop species have been approved: maize (43), potato (43), cotton (28), soybean (24), canola (20), tomato (8), alfalfa (3 events), apple (3), chicory (3), papaya (3), rice (3), sugar beet (3), rose (2), squash (2), creeping bentgrass (1), flax (1), melon (2), plum (1), tobacco (1), and wheat (1). The examples of GM crops with their traits are presented in Table 1.1. The traits such as insect resistance with *Bt* genes in maize, cotton, rice, tomato, and potato and herbicide tolerance (glyphosate tolerance) with *A. tumefaciens* strain CP4 [gene product CP4 EPSPS giving herbicide tolerant form of 5-enolpyruvulshikimate-3-phosphate synthase (EPSPS) enzyme] in soybean and alfalfa have resulted in substantial yield gains and benefits to farmers.

Table 1.1 Examples of GM traits and crops (either grown commercially or not grown commercially).

GM trait	Crop(s)
Insect resistance	Cotton, eggplant, maize, potato, poplar, sugarcane, soybean, tomato, and rice
Herbicide tolerance	Alfalfa, canola, chicory, cotton, creeping bentgrass, maize, rice, soybean, sugarbeet, and wheat
Virus resistance	Papaya and potato
Disease resistance	Potato
Altered oil composition (i.e., improved oil quality)	Canola, safflower, and soybean
Male sterility and restorer genes	Canola, chicory, and maize
Drought tolerance	Maize and rice
Nutritional or quality trait	Rice, tomato, and potato
Altered lignin	Alfalfa

This list is not exhaustive.
GM, Genetically modified.

The GM technology has been developed for value addition and nutritional quality of crop plants. Initial GM varieties had a single trait focus, which evolved to multiple genes (e.g., insect tolerance through multiple Cry proteins). In high value crops, insect and herbicide tolerance was developed. The current trend of biotech crops and traits is better stacked traits (e.g., multiple modes of herbicide resistance for a more comprehensive weed control, multiple insect species protection). This trend will likely continue and deploy multiple modes of simultaneous resistance to pests and diseases and perhaps include additional traits such as quality and climate resiliency. The current stacked trait example includes glufosinate−dicamba HT, glyphosate−dicamba HT, glyphosate−2,4-D choline tolerant, and Bt−HT. Triple herbicide tolerance is available in soybean varieties (Xtendflex) against dicamba, glyphosate, and glufosinate herbicides, Enlist E3 against glyphosate, glufosinate, and 2,4-D herbicides, and LibertyLink GT27 against Liberty, glyphosate, and 4-hydroxyphenylpyruvate dioxygenase (HPPD) inhibitors based herbicide. In maize, an eight-stack hybrid variety (SmartStax) is available with protection against corn earworm, European corn borer, southwestern corn borer, fall armyworm, corn earworm, black cutworm, along with herbicide tolerance against glyphosate, and glufosinate. However, the cost of seed generally includes the cost of technology.

The land races, wild, and weedy relatives need to be collected, conserved, and preserved; because GM technology does not replace the essence of plant breeding: useful genetic variation. The GM technology is also competing with newly emerged gene editing technique (see Chapter 27: Molecular Tools in Crop

Improvement and Cultivar Development), which provide more precision in genetic engineering without being classified as GM. The most well-known current gene editing technology is labeled clustered regularly interspaced short palindromic repeats/CRISPR-associated protein 9 (CRISPR/Cas9) system due to the protein complex used for editing DNA sequences. This technology has generated excitement due to the prospects in application and rapid acceptance as the most effective technology to change the DNA of an organism, including addition, deletion, or altering nucleotides at specific locations in the genome. The CRISPR/Cas9 system for gene editing is lower cost, faster, and higher efficiency than other existing gene editing methods, therefore, is expected to spur innovations in plant breeding.

Molecular markers in plant breeding

In the past 15−20 years molecular markers usage by plant breeders has become mainstream to introgress genes and or quantitative trait loci (QTL) in germplasm and variety development. This technique is called marker-assisted breeding (MAB) [also called marker-assisted selection (MAS)] for application in forward breeding or marker-assisted backcross breeding (MABB) [also called marker-assisted backcrossing (MABC)] to pyramid few genes/QTLs for different traits without changing the original genetic constitution of the parental cultivar. MAB is now routinely used in private and public breeding programs, for example, in most wheat breeding programs in Canada (DePauw et al., 2011). MAB has been used for traits controlled by major genes such as disease and insect resistance, for quality traits such as low cadmium content in durum wheat and high grain protein content (Table 1.2). Significant efforts have also been made in area of rice molecular breeding for drought, submergence, and salinity, the three most devastating abiotic stresses. QTLs and genes controlling these abiotic stresses have been identified and introgressed into high-yielding varieties through MAS and MABB (see Chapter 21: Breeding for Resistance to Abiotic Stresses, and Chapter 27: Molecular Tools in Crop Improvement and Cultivar Development).

For this technology to be successful, the development of markers that are in the gene (i.e., perfect markers) or very tightly linked to the gene (i.e., linked markers) and marker validation is imperative. Meta-analysis (comparing and validating QTL across genetic backgrounds and populations) to identify QTL that are relevant in breeding programs, stable in different background, and devoid of linkage drag is essential prior to their usage in plant breeding programs. This method has resulted in significant economic incremental benefit in major food crops, such as, wheat, maize, and rice. With the ongoing mapping of agronomically important genes and the development of high-throughput marker systems, the use of molecular markers in cultivar development would continue to be important in future plant breeding efforts.

Table 1.2 Examples of Western Canadian wheat cultivars registered using marker-assisted breeding (DePauw et al., 2011).

Market class	Cultivar	Registered in	Breeding institution	DNA marker or gene and trait
CWRS	Lillian	2003	AAFC, Swift current and Winnipeg	*Gpc-B1/Yr36*, grain protein
CWRS	Somerset	2004	AAFC, Winnipeg	*Gpc-B1*, grain protein
CWES	Burnside	2004	AAFC, Winnipeg	*Gpc-B1*, grain protein
CWRS	Goodeve	2007	AAFC, Swift Current	*Sm1*, midge resistance
CWES	Glencross	2008	AAFC, Winnipeg	*Sm1*, midge resistance
CWAD	Brigade	2008	AAFC, Swift Current	*Cdu1*, grain cadmium uptake
CWAD	Verona	2008	CDC, University of Saskachewan	*ScOpc20*, *Usw15*, grain cadmium uptake

Since the publication DePauw et al. (2011), numerous other cultivars have been developed using marker-assisted selection in Canada.
AAFC, Agriculture and Agri-Food Canada; *CDC,* Crop Development Centre; *CWRS,* Canada Western Red Spring; *CWES,* Canada Western Extra Strong; *CWAD,* Canada Western Amber Durum.

The current technology of next-generation sequencing (NGS) has made DNA sequencing high-throughput and cheaper. NGS provides extensive and detailed genome coverage and easier to explore and subsequently exploit the genetic and phenotypic relationships and diversity. In addition to the identification of polymorphic SNPs for MAS or MAB approaches, haplotype blocks are generated that are correlated with trait variation (quantitative). Marker saturation also allows for more powerful genome-wide association studies to identify novel genes (and markers for MAS and MAB) from diverse association panels (cultivated and landraces for identification of rare alleles) through marker trait associations. Sufficient marker numbers also facilitate genomic prediction and selection, which is a new and powerful tool in plant breeders toolkit to make selection purely on genotypic information (without phenotypic assessment) allowing selection for complex and quantitative traits (e.g., yield) in earlier generations (single plants and single short rows) minimizing time and gaining selection and breeding efficiencies. In genomic prediction, contrary to MAS or MAB approaches, all molecular markers are used to determine the individual's breeding value. The advent of NGS is also beneficial for targeted genome editing with CRISPR/Cas9 type of systems, which require knowledge of the gene sequence to be edited. This approach of genome editing is currently not considered GMO in some countries, therefore pointing to their wide application for targeted gene-trait improvement (to remove deficiency or improve trait, as the need may be). Some of the newer upcoming molecular techniques attempt to increase genetic recombination to create more genetic diversity, as well as gamete selection to make selection of gametes (based on genomic prediction) and only advancing those which meet the breeder-imposed selection criteria. These are ongoing or upcoming technologies but point to the innovative approaches in plant breeding.

Advances in image based and high-throughput phenotyping

Phenotyping remains integral to plant breeding efforts, despite the development of genetics and genomics tools. Therefore, plant breeding requires advances in phenotyping especially for traits that are difficult, time consuming, or costly to phenotype. Phenotyping involves a broad range of traits including yield, days to maturity, plant height, stem lodging, disease and insect resistance, responses to abiotic factors such as water stress (drought, flooding), heat stress, cold stress, salt tolerance, quality, and many more. The list of traits is long and can be unique to each crop species and breeding program. However, phenotyping for these traits requires experienced researchers who spend countless hours sometimes on routine repetitive tasks. Circumventing the challenges of phenotyping will allow plant breeders to work on more traits, collect timely ratings, increase population sizes, increase trait measurement accuracy, and reduce the cost of the breeding program.

With these motivations, there have been a rapid development and deployment of sensors and carrying platforms (aerial and ground) for remote and proximal sensing. These sensors include cameras that can capture more accurate and precise information at a larger scale, in a time-series, and on numerous genotypes with the advanced data analytics to tease out important insights and information (this constitutes the field of phenomics). The higher throughput phenotyping (HTP) involves the usage of sensors to rapidly collect data in an automate manner. Image-based phenotyping is one of the major methods to collect HTP data, but many other types of sensors are also available that capture information in wavelengths outside of human eye capability, generating very useful data. Sensors are deployable on both unmanned ground vehicle and unmanned aerial systems.

The cost of sensors and unmanned system is continually decreasing; therefore, these are now accessible to a larger plant breeding community. However, the adoption will depend on cost, simplicity, data accuracy, and statistical analysis capabilities (especially due to the data size and complexities). The most exciting development in data analysis domain related to plant breeding and phenotyping is machine learning (ML) (Singh et al., 2016, 2018). The ML methods are able to handle data deluge coming from digitalization of plant breeding data, as it can extract features using automated approaches. These allow generation of information at a level and scale that was previously not possible. A subset of ML tool is deep learning, which have transformed numerous things around us, including in the areas of consumer analytics, diagnostics, autonomous vehicles, and financial management. Phenomics and ML methods are revolutionizing the plant breeding pipeline, and details are provided in Chapter 28, Phenomics and Machine Learning in Crop Improvement.

Contributions of plant breeding to the world agriculture

Plant breeders have made enormous contributions to increased food production in the 20th and 21st centuries throughout the world. Along with genetic improvement of yielding ability, efforts were made to reduce maturity duration of the cultivars to fit them in multiple cropping; modify plant architecture for pure and mixed culture; insulate the cultivars against harmful parasite and extreme weather conditions (e.g., drought), soil-related stresses (e.g., salinity); and genetic enhancement of nutritional quality. For this success, both cultivated and diverse accessions (related species) have been used. This has provided stability to the yielding ability with a suite of other traits. After the World War II, plant breeders quickly responded to the human requirements and developed higher yielding cultivars and hybrids, which were cultivated using appropriate crop husbandry including the mechanization of agriculture (from seeding to harvesting) and the use of agrochemicals has accelerated the production of major field crops in the world.

From 1964 to 2014, the total area production worldwide has seen 182%, 622%, 68%, and 76% increase for cereals, oilseeds, pulses, roots, and tubers crops, respectively (source: FAOSTAT). While the yield (kg/ha) has increased 161%, 192%, 48%, and 35% for cereals, oilseeds, pulses, roots, and tubers crops, respectively, from 1964 to 2014 (Fig. 1.1, data source: FAOSTAT). The world productivity (kg/ha) of cereals, oilseeds, pulses, and roots and tubers is presented in Fig. 1.1.

In case of cereals, the increase in area during the past 50 years was only marginal (8%) but the increment in productivity was spectacular (161%) which was partly due to the large-scale cultivation of semidwarf varieties of rice and wheat, and single cross hybrids and GM cultivars in the case of maize. The oilseed crops have a noticeable rise in area seeded (147.4%) and productivity (192%), attributed to dramatic increase in soybean and other oilseed crops for their oil and meal (protein). This includes a large increase of GM soybean in the United States, Brazil, and of canola in Canada. The HT GM cultivars and non-GM cultivars may not differ significantly for their yield potential; however, GM cultivars are preferred by large acreage farmers due to their advantage in weed management practices and improving farm production systems. Although pulse crops area only increased 13.5% in 50 years (1964–2014), the yield per area increased 48% in the same period. This is due to the fact that pulse crops across the world have gained lesser emphasis of breeders and geneticists and of the funding agencies. Moreover, the pulse crops are grown largely under rainfed cropping systems, and limited private sector investments are ongoing for pulse crops. The crop species

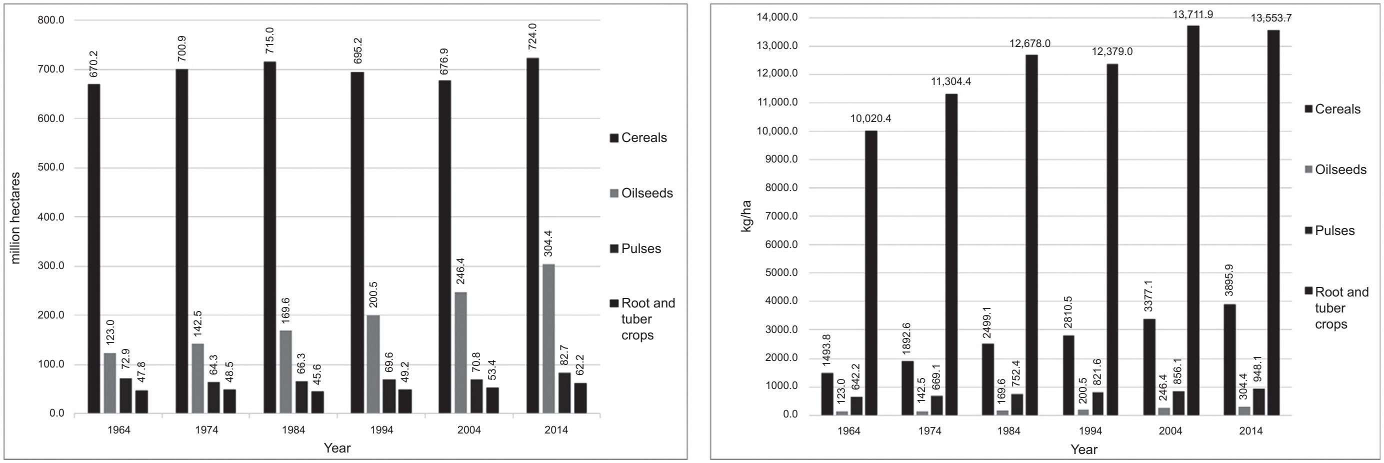

FIGURE 1.1

World production (Left graph) and productivity (Right graph) of cereals, oilseed, pulses, and root–tuber crops.

FAOSTAT, 2020. <http://www.fao.org/faostat/en/#data/QC> (accessed 05.06.20).

in category of roots and tubers group have shown an increase in area (30.3%) and productivity (35%). It is estimated that on an average a 70% yield improvement in cereals is due to genetic gains from breeding and remainder is attributed to improved farming practices, although some researchers attribute more equitable contributions to breeding and non-breeding factors. Irrespective, the role of breeding is fundamental to meet the needs of the human population in near and distant future.

Complementary role of public and private sector plant breeding

The public and private sector plant breeding have coexisted in industrialized countries over the past 100 years and both have contributed in increasing the crop yield. Public sector institutions, in general, have made contributions in the areas of basic and applied plant breeding for the benefit of society and without economic considerations. These efforts were not limited to the genetic improvement in food crops but all important crop and tree species useful to the welfare of mankind, including cereals, grain legumes, oilseeds, fiber crops, medicinal and aromatic plants, horticultural plants (vegetables, flowering plants, and fruit trees), timber trees, etc. Germplasm collection, evaluation, maintenance, preservation, and their utilization were given priority to achieve the gains. The germplasm with useful traits was made available on request to other breeders. The plant breeders and geneticists used knowledge of both the Mendelian and molecular genetics for the genetic enhancement of cultivars. Basic seeds of crop cultivars were provided to seed producing agencies for multiplication and distribution. Plant breeders in collaboration with the scientists of other disciplines have developed cultivation packages for each crop for achieving higher yields. In addition, public sector has devoted considerable resources for educating and training of plant breeders.

Private sector have worked selectively on some of the crops based on their importance in certain areas/regions and countries and profitability, for example, maize, soybean, canola, and cotton breeding is important for private sector in the industrialized world particularly the United States. Wheat is important for R&D of private companies in Western Europe, United States, Canada, and Australia, whereas canola is a priority in Canada, and cotton in some cotton growing countries. Rice is a priority in some countries of South-East Asia. Although not universally true, private sector has preferred to focus their largest R&D investments where they can protect their variety (generally GM) through a patent to ensure a more steady and protected revenue stream. These were possible through patents granted on GM traits and for crops that are not human mainstay diets.

Depending on the country and region, the relative roles of public and private plant breeding have varied. Intellectual property protection, globalization, and constraints in the funding for innovations of public sector plant breeding during the past 40−50 years have witnessed acceleration of the privatization of plant breeding, particularly in the developed countries. The discoveries in biotechnology and molecular biology disciplines, for example, increased emphasis on GM technology and molecular breeding, have reduced the activities of conventional public sector plant breeding which is somewhat concerning as they too play an important role in upstream work and product development for public good. Some of the multinational companies have made heavy investments to strengthen their capabilities in these areas and have an edge in the development of biotech cultivars of important crop species.

Future plant breeding

Population is expected to add of another 2−4 billion people to the planet within next 3−4 decades. This dictates the need to increase food production. According to Food and Agriculture Organization (FAO) estimate mostly in developing countries, food production must increase by 60% between now and 2050 to meet the demands. However, the amount of arable land is not likely to increase much in future because of increasing urbanization, salinization, and desertification. Average temperatures and dry land areas are predicted to expand in arid and semiarid tropics, which occupies about 40% of land area. In future, freshwater availability for irrigation would also be scarce. Global climatic changes can affect the crop productivity. An optimum temperature range is required for an optimum growth and development of the crop as well as for sink to accumulate starches, proteins, and fats. Schlenker and Roberts (2009) reported that yields increase with temperature up to 29°C for corn, 30°C for soybeans, and 32°C for cotton in the United States, but they would decline precipitously at higher temperatures. They predicted that yields of these crops in the current growing areas will decline by 30−46% by the end of the 21st century under most moderate climate change and by 63−82% under most warming scenario. It is estimated that even an increase of 1−2°C temperature would have dramatic deterioration in yields of the food crops and most dramatic impacts are expected in the arid zones. Flood prone regions of South-East Asia would also be worstly affected due to climatic changes. In view of above reasons, plant breeding priorities need to be redefined and strategized to be future looking. An important strategy would be to increase yielding abilities of crops vertically and to continue doing so, not only of major food crops but also of so-called minor crops especially the ones that were ignored during the era of green revolution. The ways and means of increasing the food production and the productivity of the food crops through plant breeding research are briefly described herewith.

One of the negative impacts of green revolution was widespread cultivation of only few crop species and their fewer cultivars which resulted in the genetic homogenization. Millets, small millets, and pulse crops are grown traditionally by small and marginal farmers under rainfed conditions which are stressful environments where major cereals (rice, wheat, and maize) fail. These crops were less attended by plant breeders and were somewhat ignored by policy makers and funding agencies during and after the green revolution era. Therefore, these crops need to be revisited for their genetic improvement. Major millets, which include sorghum (*Sorghum bicolor*) and pearl millet (*Pennisetum glaucum*), and small millets, which include finger millet (*Eleusine coracana*), foxtail millet (*Setaria italica*), kodo millet (*Paspalum scrobiculatum*), proso millet (*Panicum miliaceum*), barnyard millet (*Echinochloa esculenta* and *Echinochloa frumentacea*), and little millet (*Panicum sumatrense*), are valued for their nutritional quality and health benefits. In general, small millets provide reasonable and assured harvest under low inputs and most adverse climatic conditions. Millets are C_4 crops and hence are climate change compliant (NAAS, 2013). In Table 1.3 important traits of adaptation to adverse climatic and soil conditions of small millets are presented. Small millets, in general, are suitable for rainfed areas and dry land agriculture. Some of the cultivars of these millets are early maturing, suitable as catch crop.

Grain legumes (pulse crops; family—Leguminosae) occupy a unique position in the world agriculture by virtue of their 2-3x higher seed protein content than cereals. These crops have wider adaptation under stress prone marginal conditions, due to their capacity to fix atmospheric nitrogen (30−150 kg/ha) symbiotically in association with *Rhizobium* bacteria (Table 1.4). For many of the developing countries in the world, pulses constitute a cheap and readily available source of dietary protein, and is produced in an environmentally sustainable manner. Therefore, the only practical avenue to solve protein malnutrition problem in these countries is to significantly increase the productivity and total production of these crops. In the developed world, soybean [*Glycine max* L. (Merr.)] is an indirect source of protein as they are used in animal feed. Although soybean and peanuts belong to the family Leguminosae, as per the FAO, they are classified as oilseed crops but both are desirable for their oil (cooking and industrial applications) and protein (feed applications and food source) content. Pulse crops do not include legume crops that are

Table 1.3 Small millets and their adaptation ability traits to extreme climatic and adverse soil conditions.

Crop	Adaptation ability to abiotic stresses
Barnyard millet	It is able to grow on poor soil and is tolerant to cold.
Finger millet	It is tolerant to drought and salt stresses.
Foxtail millet	It is tolerant to drought and salt stresses.
Kodo millet	It is tolerant to drought and can be grown on poor soils from gravelly to clay.
Little millet	It is well adapted to regions with less rainfall and is tolerant to drought, pests, and salts.
Proso millet	It is well adapted to clay sandy soils.

Table 1.4 Adaptation ability of important pulse crops and soybean to climatic and edaphic conditions.

Crop	Adaptation ability to abiotic stresses
Chick pea	Tolerant to drought and low management, large seed variation.
Cow pea	It is grown on wide range of soil types (sandy to heavy clay).
Lentil	It can be grown on poorer soils and even on soils of moderate alkalinity. It can tolerate drought conditions.
Mung bean, Urd bean	These are grown widely in various agroclimatic zones and cropping systems.
Peas	It thrives well in places with cool climate and is grown on wide variety of soils types.
Pigeon pea	Better adapted to marginal climatic conditions. Its roots open up the soil and improve the soil structure.
Soybean	Very wide adaptation from tropics to temperate regions, and large variation in days to maturity.

harvested green (such as green peas, green beans, and edamame as these are classified as vegetable crops), and crops that are planted exclusively for sowing (cover crops) purposes (such as clover and alfalfa).

Pulse crops, soybean, and peanuts (*Arachis hypogaea*) can meet the needs of a growing population. Important pulse crops that need immediate attention of plant breeders are chickpea (*Cicer arietinum*), pigeon pea (*Cajanus cajan*), urd bean (*Vigna mungo*), mung bean (*Vigna radiata*), cow pea (*Vigna unguiculata*), lentil (*Lens culinaris*), peas (*Pisum sativum*), common bean (*P. vulgaris*), and faba bean (*Vicia faba*). Similarly, breeding efforts and resources are needed in soybean and peanut. These crops have a rich genetic diversity. The genetic enhancement in the yielding ability and production of these crops that would facilitate their easy availability to poor people which in turn would help in decreasing the number of malnourished people of rapidly growing populations in underdeveloped and developing countries. With a rapidly emerging interest in plant protein diets, and moving away from more energy intensive animal protein, pulse crops are expected to play a huge role in human diet in coming years.

The genetic improvement of millets and pulses would pave the way for ushering the second green revolution by developing higher yielding and climate resilient varieties of these crops. Pulse, oilseed, and millet crops need R&D investment by federal, state, private, and foundations, with special emphasis on crop breeding and related research.

Plant breeders have made tremendous progress during the past 75 years in the genetic enhancement of yield traits, nutritional quality, disease, and insect–pest resistance, which increased crop production and productivity of major food crops. However, rarely cultivars are insulated against the adverse environmental stresses that are now increasingly becoming more important due to climate change. The climatic changes would not only affect the yield *per se* but also the end-use quality. It will affect the prevalence and severity of harmful parasites and in turn the host–parasite interactions. Therefore, both biotic and abiotic stresses are to be identified together and given due attention. There is an urgent need to search genetic variation in crop species for agroclimatic factors (e.g., drought, heat, cold, and flood) and soil-related stresses (e.g., mineral deficiencies and toxicities, saline, and acidic soils). The recent research advances in the areas of biotechnology, genomics, and phenomics will not replace conventional plant breeding in public and/or private sector. Instead, these are tools that will aid in the development of superior cultivars of all food, feed, fiber, and fuel crops with multiple modes of resistance to pests/diseases and to abiotic stressors, improved nutritional quality (for food crops), and high yield potential with plasticity (stable and responsive against myriad conditions).