1
Introduction

1.1 Requirements of plant breeders

The aim of plant breeding is to develop genetically superior cultivars that are adapted to specific environmental conditions and suitable for economic production in a commercial cropping system. These new, and more productive cultivars, are increasingly necessary to fulfil humankind's escalating needs for food, fibre and fuels.

The basic concept of varietal development is rather simple and involves three distinct operations:

- produce or identify genetically diverse germplasm from which segregating breeding populations are developed;
- carry out selection procedures on phenotypes or genotypes from within this germplasm to identify superior genotypes with specific improved characteristics;
- stabilize and multiply these superior genotypes and release cultivars for commercial production.

The general philosophy underlying any breeding scheme is to maximize the probability of creating, and identifying, superior genotypes which will make successful new cultivars; in other words, genotypes that will contain all the desirable characteristics/traits necessary for use in a given production system, or at least offer a beneficial trade-off between key advantageous characteristics compared with undesirable ones.

Plant breeders can be categorized into two types. One group of plant breeders is employed within private companies, while the other group works in the public sector (e.g. government-funded research institutes or universities). Private sector and public sector breeders often have different approaches to the breeding process. Many of the differences that exist between public and private breeding programmes are related to the time available for variety release, types of cultivar developed, and priorities for traits in the selection process.

Plant breeders within the public sector are likely to have a number of responsibilities related to academic activities or extension services, in addition to those solely directed towards producing new varieties. Public sector breeders also play an additional, often unappreciated yet critical role: the attraction, training and development of a younger generation of men and women interested in plant breeding. As plant breeding is a combination of science and art, the personal component of training plant breeders at the graduate level is generally recognized as more relevant and significant than in most other areas of science.

Private sector plant breeders tend to have a more clearly defined goal: developing new cultivars and doing it as quickly as possible. In addition, many private breeding organizations are, or are associated with, biotechnology and/or agrochemical companies. As a result, varietal development may be designed to produce cultivars suitable for

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integration within a specific production system. In many countries, including the US, the ratio of private to public breeders has increased over time, particularly in those highest acreage crops such as maize, soybeans and canola, to mention just a few, as well as in crops with a high profit, such as tomato, pepper and lettuce, where private companies can gain greatest financial returns from seed or chemical sales.

Despite the apparently simple description of the breeding process given above, in reality plant breeding involves a multidisciplinary and long-term approach. Regardless of whether a breeding scheme is publicly or privately managed, a successful plant breeder will require knowledge in many (if not all) of the following subjects:

Evolution It is necessary to have knowledge of the origins and past progress in adaptation of crop species if additional advances are to continue into the future. When dealing with a crop species, a plant breeder benefits from knowledge of the timescale of events that have modelled the given crop. For example, the time of domestication, geographical area of origin and prior improvements are all important and will help in setting feasible future objectives. In the case of crops where hybridization systems are commercially available, such as canola and corn, the evolution from OP (open pollinated) to hybrid cultivars represents a landmark driving profound changes in ensuing breeding programmes.

Botany The raw material of any breeding scheme is the available germplasm (lines, genotypes, accessions, etc.) from which agronomically relevant variation can be exploited. The biological relationship that exists within a species and with other species will be a determining factor indicating germplasm variability and availability.

Biology Knowledge of plant biology is essential to create genetic variation and formulate a suitable breeding and selection scheme. Of particular interest are modes of reproduction, types of cultivar and breeding systems.

Genetics The creation of new cultivars requires manipulation of genotypes and genes. The understanding of genetic processes is therefore essential for success in plant breeding. Genetics is an ever-developing subject, but knowledge and understanding that is particularly useful will include single gene inheritance, population genetics, the expected frequencies of genotypes under selection, and the prediction of quantitative genetic parameters – all of which will underlie decisions on what strategy of selection will be most effective.

Pathology A major goal of plant breeding is to increase productivity and quality by selecting superior genotypes. A limiting factor in economic production is the impact of pests and diseases. Therefore developing cultivars that are resistant to detrimental pathogens has been a major contributor to most cost-effective production with reduced agrochemical inputs. Similarly, nematodes, insect pests and viruses can all have detrimental effects on yield and/or quality. Therefore plant breeders must also have knowledge of **phytopathology**, **nematology**, **entomology** and **virology**.

Weed science The response of a genotype to competition from weed populations will have an effect on the success of a new cultivar. Cultivars that have poor plant establishment, or lack subsequent competitive ability, are unlikely to be successful, particularly in systems where reduced, or no, herbicide applications are desirable, or their use is restricted. Similarly, in many cases genotypes respond differently, even to selective herbicides. Herbicide tolerance in new crops is looked upon favourably by many breeding groups, although cultivar tolerance to broad-spectrum herbicides can cause management difficulties in crop rotations. Herbicide tolerance brought about by traditional breeding as well as through recombinant DNA techniques has also driven changes in plant breeding approaches.

Food science Increasingly end-use quality is being identified as one of the major objectives of all crop-breeding schemes. As most crop species are grown for either human or animal consumption, knowledge of food nutrition and other related subjects is important.

Biometry Managing a plant-breeding scheme has aspects that are no different from organizing a series of large experiments over many locations and years. To maximize the probability of success it is necessary to use an appropriate experimental approach at all stages of the breeding scheme. Plant breeding is continually described as ‘a numbers game’. In many cases this is true, and successful breeding will result in vast datasets on which selection decisions are to be made. These decisions often have to be made under significant time constraints, for instance between harvesting one crop and planting another. Therefore, plant breeders are required to be good **data managers**.

Agronomy It is the aim of crop breeders to predict how newly identified genotypes will perform over a wide range of environments. This will require research into agronomic features that may relate to stress tolerance, such as heat, drought, moisture, salinity and fertility. These experiments are essential in order that farmers (the primary customer) are provided with the optimal agronomic husbandry parameters, which will maximize the genetic potential of the new variety. Poor agronomic practice can detrimentally affect the expression of genotypes and the selection of appropriate phenotypes. Despite increasingly powerful statistical tools, poorly managed field trials represent a waste of effort and a risk of reducing the rate of genetic gain expected.

Molecular biology Advances in molecular biological techniques are having an increasing role in modern plant breeding. Molecular markers are increasingly used by plant breeders to help select (indirectly and directly) for characteristics that are difficult to evaluate in the laboratory, or are time-consuming or expensive to determine accurately on a small plot scale. Genetic engineering and tissue culture operations, such as the development of double haploid populations, are becoming standard in many plant-breeding schemes, and it is likely that further advances will be made in the future. Knowledge of all these techniques and continued awareness of ongoing research will be necessary so that new procedures can be integrated into the breeding scheme where appropriate. In those crops where transgenic variation is commercially available, such as herbicide or insect tolerance in corn, the availability of molecular markers has enabled the development of effective schemes collectively known as trait integration, where a small genomic region carrying a transgenic trait is very quickly introgressed into elite germplasm without detrimental effects on other traits which are also important for farmers.

Love for working in the field Despite continuing progress in biotechnology and the availability of statistical tools, there remains no substitute for applied field research and crop performance evaluation. Field crops, by definition, are produced commercially under field conditions, and plant breeders will rely heavily on field plot research for phenotypic evaluations. Therefore, plant breeders must be willing to spend significant time visiting field trials and nurseries, seeing how different phenotypes develop, learning how biotic and abiotic stresses build up in the field, and gaining a deep insight into how plants interact with and respond to the environment. The late Nobel Peace Prize winner Norman Borlaug said: "*Plants speak to human beings. However, they only whisper softly like a woman of great culture. They hence reveal their secrets only to those who are close to them. Those who spend their time in office rooms naturally think that plants are dumb*." This is as relevant today as it was many years ago.

Production The contributions that farmers and other growers have made to varietal development should never be underestimated. It should also be noted that growers are the first customers for plant breeding products. The probability of a new cultivar being successful will be maximized (or at least the probability of complete failure reduced) if growers and production systems are considered as major factors when designing breeding systems.

Management There is a need to manage people, time and money. It has already been stated that plant breeding is a multidisciplinary science, and this means being able to integrate and optimize people's effort to effectively use breeders' time. The length of most breeding programmes means that small proportional savings in time can be valuable, and it hardly needs emphasizing that breeding needs to be cost-effective and therefore the cost of the programme is always going to be important.

Communication Most varietal development programmes consist of inputs from more than one scientist, and so it is necessary that plant breeders are good communicators. Verbal and written communication of results and test reports will be a feature of all breeding schemes. Research publications and grant proposals are of major importance, particularly to public breeders, if credibility and funding is to be forthcoming. In the case of private breeders, they have to be able to establish good communication links with their business counterparts. In addition, there has been an increasing need for plant breeders to be able to communicate with other stakeholders, like administrators, politicians and society at large, in order to raise awareness about the importance of plant breeding and therefore attract the funding needed to sustain breeding efforts. Finally, at least some plant breeders must be good educators and have the ability to pass on essential information about the subject to future plant breeders.

Information technology The science underlying plant breeding is continually advancing, agronomic practices are continually being upgraded, the end-users' choices change, and the political context continually affects agriculture. This means that it is vital that breeders talk to these different groups of people, but also use whatever technology is available to keep up to date with developments as they occur – or better, before they occur! Information technology enables breeders to capture, manage and analyze ever-increasing datasets, and also to identify the genetic signal buried in experimental noise. As an example, bar code devices are playing an increasing role in the high throughput collection of plant phenotypes, and so reducing the rate of involuntary mistakes.

Psychic The success of most plant breeding schemes is not realized before many years of breeding and trialling have been completed. It may be 10 or more years between the initial crosses and varietal release. In the extreme case of, say, oil palm or fruit tree breeders, they might not live to see the results of the plant selections they have made. Plant breeders therefore must be *crystal ball gazers* and try to predict what the general public and farming community will need in the future, what progress biotechnology will bring about in the years to come, what diseases will persist in years ahead, and what quality characters will command the highest premiums. The experience that plant breeders accumulate enables them to augment the quality of decisions purely based on those scientific disciplines supporting any breeding programme.

In summary, therefore, successful plant breeders need to be familiar with a range of scientific disciplines and management areas. It is not, however, necessary to be an expert or indeed an authority in all of these. However, greater knowledge of the basic science underlying the techniques employed, and of the plant species concerned, in terms of the biology, genetics, history and pathology, will increase the chances of a breeder succeeding in developing the type of cultivars most suitable for future exploitation.

1.2 Evolution of crop species

Plant breeding consists of the iterative process of creation and manipulation of genetic variation within a crop species, and selection of desirable recombinants from within that variation. The process is therefore an intensification of a natural process, which has been ongoing since humans first appeared on earth. Plant breeders utilize and accelerate the evolutional process by directing it towards the increasing needs of humankind. As soon as humans began settled agriculture they effectively, albeit unconsciously, started plant breeding. In this section the main features of crop plant evolution will be covered briefly. The study of evolution is a vast and detailed subject in itself, and it will not be possible to cover more than an introduction to it in this book. Emphasis will be on the areas that are most important from a plant breeding standpoint.

Knowledge of the evolution of a plant species can be invaluable in breeding new cultivars. Studies of evolution can provide knowledge of the past changes in the genetic structure of the plant, an indication of what advances have already been achieved or might be made in the future, and help to identify relatives of the domesticated plant which could be used in interspecific or intergeneric hybridization to increase genetic diversity or introduce desirable characters not available within existing crops.

1.2.1 Why did hunter-gatherers become farmers?

It is difficult to arrive at a firm understanding as to why humans became a race of farmers. Early humans are believed to have been foragers and later hunters. Why then did they become crop producers? Farming is believed to have started shortly after the last ice age, about 10,000 years ago.

At that time there may have been a shortage of large animals for hunters to hunt, due to extinctions. Indeed, little is known about the order of agricultural developments. Did man domesticate animals and then domesticate crops to feed these beasts, or were crops first domesticated, and from this the early farmers found that they could benefit from specifically growing sufficient food to feed livestock? The earliest farmers may also have been fishermen who tended not to travel continually and were more settled in one region. In this latter case, perhaps the first farmers were women who took care of the farming operation while the males fished and hunted locally. It may simply have been that some ancient people became tired of nomadic travel in search of food, became bored with living in tents and opted for a quiet life on the farm! The answers are not known, although it can often be interesting to postulate why this change occurred. One misconception about the switch from hunting-gathering to farming is that farming was easier. It has been shown that gathering food requires considerably less energy than cultivating and growing crops. In addition, skeletal remains show that the initial farmers were smaller-framed and more prone to illness than their hunter-gatherer counterparts.

Regardless of the reason that caused mankind to cultivate crops, few would question that the beginning of farming aligned with the beginning of what most of us would consider civilization. Farming created communities, community structure and economies, group activities, enhanced trade and monetary systems, to name but a few. There is also little doubt that the total genetic change achieved by early farmers in moulding our modern crops has been far greater than that achieved by the scientific approaches that have been applied to plant breeding over the past century. Given that these early farmers were indeed cultivating crops, it is not surprising that they would propagate the most productive phenotypes, avoid the individuals with an off-taste or hard seeds, and choose not to harvest those plants that were spiny. Even today among peasant farmers there is a general trend to select the *best plants* for resowing the next year's crops. Early farmers may have used relatively sophisticated plant breeding techniques as there is evidence that some Native Americans have a long-established understanding of maintaining pure line cultivars of maize by growing seed crops that are isolated from their production fields.

1.2.2 What crops were involved? And when did they arise?

Today's world food production is dominated by small grain cereal crops, with world production of maize (*Zea Mays*), rice (*Oryza sativa*) and wheat (*Triticum* spp.) each being just above 600 million metric tonnes annually (Figure 1.1). Major root crops include potato (*Solanum tuberosum*), cassava (*Manihot esculenta*), and sweet potato (*Ipomoea batatas*). Oilseed crops include soybean oil (*Glycine max*), oil palm (*Elaeis guineensis*), coconut palms (*Cocos nucifera*) and canola (*Brassica napus*). World production of fruit and vegetables are similar, where tomato (*Lycopersicum esculentum*), cabbage (*Brassica oleracea*) and onion (*Allium* spp.) are leading vegetable crops, whilst orange

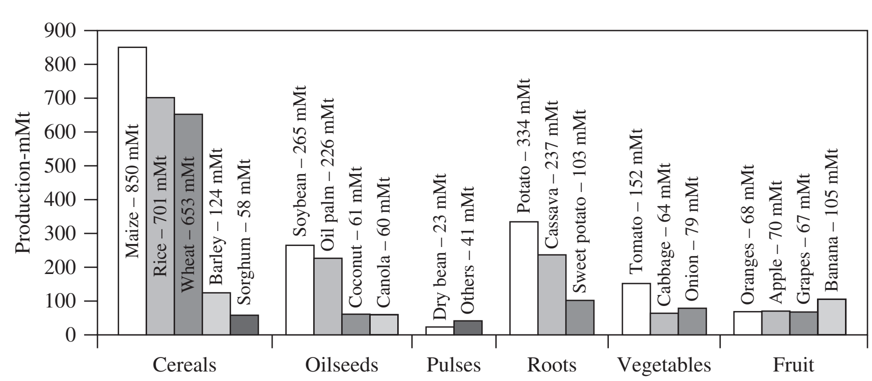

Figure 1.1 World production of major crops.

(*Citrus sinensis*), apple (*Malus* spp.), grape (*Vitis* spp.) and banana (*Musa acuminata* and *M. balbisiana*) predominate amongst the fruits. Many of these modern day crops were amongst the first propagated in agriculture.

Many studies have been made to determine the date when humans first cultivated particular crops. The accuracy of dating early remains of plant tissue has improved over the past half century with the use of radiocarbon methods. It should, however, be noted that well-preserved archaeological plant material has not proved easy to find. Many of the most significant findings have been from areas of arid environments (e.g. the eastern Mediterranean and Near East, New Mexico and Peru). These arid regions favour the preservation of plant tissue over time, and, not surprisingly, are the areas where most archaeological excavations have taken place. Conversely, there is a lower probability of finding well-preserved plant remains in regions with wetter and more humid climates. Therefore, archaeological information may provide an interesting, but surely incomplete, picture.

A summary of the approximate time of domestication and centre of origin of the world's major crop species, and a few recent crop additions, is presented in Table 1.1. It should be reiterated that many crop species have more than one region of origin, and that archaeological information is continually being updated. This table is therefore very much an oversimplification of a vast and complex picture.

Some of the earliest recorded information showing human domestication of plants comes from the region in the Near East known as the 'Fertile Crescent' (including the countries of Turkey, Syria, Israel, Iran and Iraq). Domestication of crops in this region surrounding the *Tigris River* began before 6000–7000 BC. Two of the world's leading cereal crops, einkorn and emmer wheat, as well as barley, have their centre of origin in this region. In addition, archaeological remains of onion, peas and lentils, dating back over 7,000 years have all been found within the Fertile Crescent. In the Americas, similar or slightly later dates of cultivation have been shown for beans and maize in central Mexico and Peru, and potato, cassava, and sweet potato in Peru, Chile and western South America. Sunflower (*Helianthus*) is the only major crop species with a centre of origin in North America, and indeed most other crops grown in the US and Canada evolved from other continents. Rice, soybean, sugarcane (*Saccharum* spp.), and the major fruit species (orange, apple and banana) were all first domesticated in China and the Asian continent a few millennia BC. Examination of archaeological remains shows that the dates of crop domestication in Africa were later, yet sorghum, oil palm and coffee are major world crops that have their centre of origin in this continent. Similarly, cabbage and a few other vegetable crops have their centre of origin in Europe. Given more research, it may be found that many more of today's crops were domesticated at even earlier periods.

Several crops of importance have been domesticated relatively recently. Sugar beet was not grown commercially in Europe until the 18th century, while rubber, oil palm and coconut palms were not domesticated until the end of the 19th century. The forage grasses, clovers, and oilseed rape (*Brassica napus* L. or *B. rapa* L.) are also recently domesticated crops, although some researchers would argue that these crops have yet to make the transition necessary to be classified as truly domesticated. New crops are still being recognized today. The advent of bioenergy crops has identified the oilseed crop camelina (*Camelina* spp.), and the biomass crop switchgrass (*Panicum virgatum*) as potential new crops species which have yet to be grown in large-scale commercialization.

A high proportion of today's major crops come from a very small subsample of possible plant species (Figure 1.1). It has been estimated that all the crop species grown today come from 38 families and 91 genera. This restriction in our plant-based diet is of concern because it potentially limits the consumption of the key nutrients supplied by plants and increases our dependence on animal products. Therefore, although the source of our present-day crops may be more diverse than we have shown, they still only represent a fraction of the total families and genera which have been estimated to exist within the angiosperms as a whole. Also, it should be noted that the sources of origin of these crops are spread over Europe, the Near East, Asia, Africa and America.

At some time in the past, each of our present-day crop species must have originated in one or more specific regions of the world. Originally it was thought that there were only 12 major centres of origin including the Near East, Mediterranean,

Table 1.1 Estimated time of domestication and centre of origin of major crop species.

Crop	Length of time domesticated (years)	Possible region of origin
Cereals		
Maize, *Zea mays*	7,000	Mexico, Central America
Rice, *Oryza sativa*	4,500	Thailand, Southern China
Wheat, *Triticum* spp.	8,500	Syria, Jordan, Israel, Iraq
Barley, *Hordeum vulgare*	9,000	Syria, Jordan, Israel, Iraq
Sorghum, *Sorgum bicolor*	8,000	Equatorial Africa
Oilseeds		
Soybean, *Glycine max*	2,000	Northern China
Oil palm, *Elaeis guineensis*	9,000	Central Africa
Coconut palm, *Cocos nucifera*	100	Southern Asia
Rapeseed, *Brassica napus*	500	Mediterranean Europe
Sunflower, *Helianthus annuus*	3,000	Western United States
Pulses		
Beans, *Phaseolus* spp.	7,000	Central America, Mexico
Lentil, *Lens culinaris*	7,000	Syria, Jordan, Israel, Iraq
Peas, *Pisum sativum*	9,000	Syria, Jordan, Israel, Iraq
Root crops		
Potato, *Solanum tuberosum*	7,000	Peru
Cassava, *Manihot esculenta*	5,000	Brazil, Mexico
Sweet potato, *Ipomoea batatas*	6,000	South Central America
Sugar beet, *Beta vulgaris*	300	Mediterranean Europe
Vegetables		
Tomato, *Lycopersicum esculentum*	3,000	Western South America
Cabbage, *Brassica oleracea*	3,000	Mediterranean Europe
Onion, *Allium* spp.	4,500	Iran, Afghanistan, Pakistan
Fruit		
Orange, *Citrus sinensis*	9,000	South-east Asia
Apple, *Malus* spp.	3,000	Asia Minor, Central Asia
Grape, *Vitaceae* spp.	7,000	Eastern Asia
Banana, *Musa acuminata, M. balbisiana*	4,500	South-east Asia
Others		
Cotton, *Gossypium* spp.	4,500	Central America, Brazil
Coffee, *Coffea* spp.	500	West Ethiopia
Rubber, *Hevea brasiliensis*	200	Brazil, Bolivia, Paraguay
Alfalfa, *Medicago sativa*	4,000	Iran, Northern Pakistan

Afghanistan, the Pacific Rim, China, Peru, Chile, Brazil/Paraguay and the US. More recent research has altered this original view, and it is now apparent that:

- Crops evolved in all regions of the world where farming was practised.
- The centre of origin of any specific crop is not usually a clearly defined geographical region. Today's major crops are more likely to have evolved over large areas.
- Early farmers and nomadic travellers would have been responsible for widening the region where early crops have been found and added confusion concerning the true centres of origin.
- Regions of greatest crop productivity are rarely related to the crop's centre of origin.

Overall, therefore, domesticated crops have originated from at least four of the six world continents (America, Europe, Africa and Asia). Australian aborigines remained hunter-gatherers and did not become farmers, and indeed farming in Australia is a relatively new activity started after western settlers arrived there. Not surprisingly, therefore, few of today's major agricultural crops originated in Australia; however, a recently domesticated crop (macadamia nuts) does have its origin in this continent.

1.3 Natural and human selection

All domesticated crops have been developed from wild, "weedy" ancestors. Early farmers modified wild species into modern-day crops through a process of genetic manipulation and selection. As a result these crop species have been sufficiently altered such that they can be considered to be domesticated. A definition of domestication has been given by the late Professor N.W. Simmonds as follows: "*a plant population has been domesticated when it has been substantially altered from the wild state and certainly when it has been so altered to be unable to survive in the wild*". The first part of this definition can certainly be readily accepted for almost all modern-day agricultural crops, although we still propagate many crops (e.g. date palm) where the crop species are modified only slightly from ancient ancestors. It is not always possible to relate domestication to a lack of potential to survive in non-cultivated situations, since many commercially grown plants survive as volunteer weeds, or "escapes", in either the same, or different, regions to those in which they are most commonly grown commercially. Nevertheless, their ability to compete against other plants, to withstand pests and/or diseases or to prosper in soils lacking mineral fertilizers or water is less than that observed in feral populations of the same plant species.

In the evolution of crop species we can often distinguish between natural and human selection. Natural selection tends to favour the predominance of the most adapted plant types, which manage to reproduce and disperse their progeny while tolerating the stress factors that prevail in a particular environment. Therefore natural selection favours plant phenotypes which have the greatest chance of survival, reproduction, and distribution of progeny. For example, wild cereal plants tend to have many small seeds at maturity and disperse their seed by shattering. These seeds are also likely to be attached to a strong awn to aid dispersal. Similarly, wild potato species produce many small tubers, have their tubers develop at the end of very long stolons (so that daughter plants do not occupy ground too close to the parent), and many have tubers with high levels of toxin, which discourage animals from eating them.

Human selection is the result of conscious decisions by a farmer or plant breeder to keep the progeny of a particular parent and discard others. Human selection is not usually directed to better survival in the wild (and indeed is often detrimental to survival outside cultivation). As an example, breeders have developed cereal cultivars which have fewer but larger seeds that do not shatter their seeds at maturity, and that have a non-persistent awn. Similarly, potato breeders have selected plants with fewer but larger tubers, shorter stolons, and with reduced levels of toxins in the tuber. Human selection has also produced crops that are more uniform in the expression of many of their characteristics. For example, they have selected seeds that all mature at the same time, with uniform germination, and fruits with uniform fruit size, colour and shape. In more recent times plant breeders' selection has tended to result in shorter plants, greater harvest index (the ratio of harvested product dry matter to the total dry matter produced to sustain such harvested product), and increased ease of harvest. In addition, plant breeders have been able to either reduce or extend growth cycles, or to develop photoperiod insensitive cultivars. A large number of our crop species that used to require harvest by hand can now be harvested by machine, mainly as a consequence of their small stature and uniform ripening.

There is of course a range of characteristics that would have been positively selected both by natural evolution and early plant breeders. These might include aspects of yield potential, tolerance to stress factors, and resistance to pests and diseases.

1.4 Contribution of modern plant breeders

Around the turn of the 20th century the foundation of modern plant breeding was laid. Darwin's ideas on the differential survival of better adapted types were combined with those of Mendel on the genetic basis for the inheritance of plant characteristics. These two theories, combined with the research of scientists such as Weissman on the continuity of germplasm, the analyses of Johannsen resulting in the idea of genotype/phenotype relationships, and the rediscovery of Mendel's laws by Bateson, provided the scientific foundation of modern plant breeding.

There is little doubt that mankind has had a tremendous influence in moulding the morphology, plant types, end uses, and productivity of most crop species. Early farmers have taken wild, weedy plants and developed them into domesticated crops. The contribution of modern plant breeding efforts is not always clearly defined, nor can the achievements easily be measured.

Over the past century the world's human population has risen dramatically (Figure 1.2). World human population first exceeded one billion in 1804. It took a further 118 years of population expansion to double the world population. The human generation born after World War II (1945 to 1955) are often referred to as 'baby boomers'. Interestingly, this is the first generation to witness the world's population double, from 3 billion to 6 billion individuals. It has further been estimated that within the next 20 years another 2 billion people will inhabit this earth, and that the Earth's population is predicted to reach over 9 billion people by 2050. At the time of writing, the seventh billion person has already arrived on planet Earth.

Population explosion, combined with mass urbanization, and proportionally fewer farmers, led to fears from world population specialists of worldwide hunger and famine. However, since the start of the 'baby boom' era, the yield of almost all of our major agricultural crops has increased as dramatically as the human population. Cereal and oilseed crop production have doubled since 1955 (Figure 1.3). Similar increases in vegetable production of 235%, fruit production of 28%, pulses by 51% and root crops by 50% have taken place in a 56 year time span. When world agricultural production is adjusted according to population increase (Figure 1.4), cereal production per capita has increased by 19%, and fruit, vegetable, and oilseed production per capita has increased by 57%, 146% and 200%, respectively, while production of root crops and pulses has reduced per head of capita in the world. However, these significant increases in food production cannot distract us from the overwhelming challenges lying ahead: if populations increase at the predicted rate, then it has been estimated that during the next 50 years agriculture will have to produce an equivalent amount of food to that produced during the last 10,000 years combined.

These yield increases have been brought about by a combination of improved soil fertility (mainly due to additions of inorganic nitrogen fertilizers), improved chemical control of diseases and pests, better weed control through improved agronomic practices and herbicides, and better crop agronomic practices (e.g. correct plant densities), as well as by growing genetically improved cultivars.

So, how much of the improved yield can be attributed to the plant breeder (i.e. genetic change) and how much to better farming practices (i.e. environmental change)?

Yield increases of more than 100% have been found between single cross maize hybrid cultivars

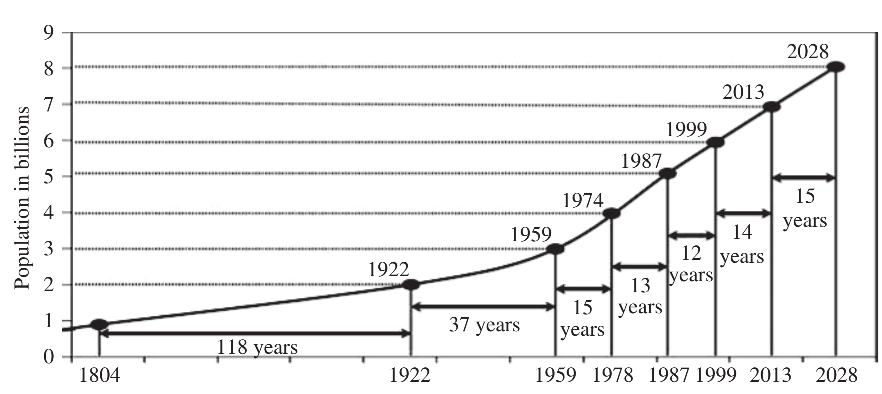

Figure 1.2 World population increase.

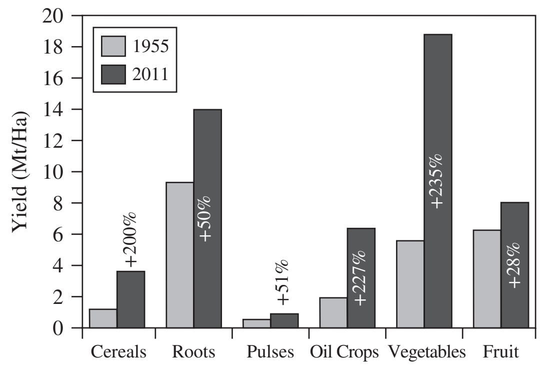

Figure 1.3 Total world crop production, 1955 and 2011.

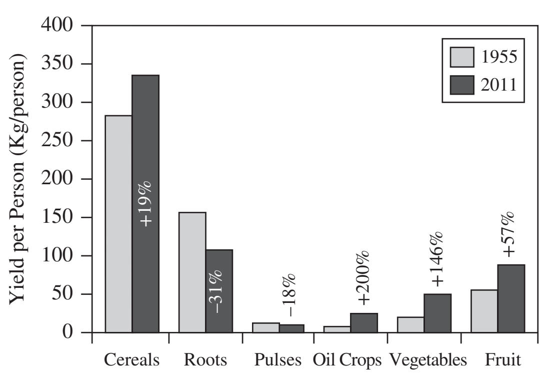

Figure 1.4 Total world crop production per capita, 1955 and 2011.

over the traditional open pollinated varieties. Many researchers have attributed this increase to the heterotic advantage of single crosses over homozygous inbred lines, and therefore conclude that the contribution of plant breeding must be very high. However, a complication arises when comparing single cross hybrids, where selection has been aimed at maximum hybrid productivity, against inbred lines which have been chosen for their combining ability rather than their own performance *per se*.

It might be suggested that the question could only be answered properly by growing a range of old and new varieties under identical agricultural conditions. Since most modern cultivars are dependent upon high levels of soil fertility and the application of herbicides, insecticides and fungicides, these would have to be used in the comparison trial. However, older cultivars were not grown under these conditions. Certainly, older cereal varieties tend to be taller than newer ones and are therefore more prone to lodging (flattening by wind or rain) when grown under conditions of high soil fertility. These considerations also show that cultivars are bred to best utilize the conditions under which they are to be cultivated. Nevertheless, several attempts to compare old and new cultivars have been undertaken in an attempt to determine the contribution of modern plant breeding to recent yield increases.

In one comparison carried out in the United Kingdom, winter wheat cultivars ranging in introduction date from 1908 to 1980 were simultaneously evaluated in field trials. In a similar experiment, spring barley cultivars ranging in introduction dates from 1880 to 1980 were compared. From the wheat cultivars available in the mid-1940's the grain yield from this study was about 5.7 t ha^{-1} but from the most recently introduced cultivars from 1980, yields were about 50% higher. There was a similar improvement in barley yield over the same period of about 30%. Therefore, considering these studies, we can reasonably conclude that breeding has contributed about half to the more-than-doubled cereal yield between 1946 and 1980.

In contrast, a study carried out in potatoes, with cultivars with dates of introduction from 1900 to 1982 (Figure 1.5), found that modern plant breeding

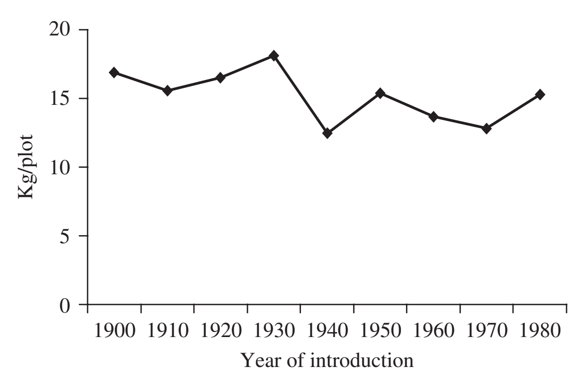

Figure 1.5 Saleable yield of tubers from potato cultivars grown over a three-year period. Yield is related to the year that each cultivar was introduced into agriculture.

had been responsible for a very small contribution to the more-than-doubled potato yield in the UK. This study in potato may, in part, reflect why 'Russet Burbank', introduced before 1900, still dominates potato production in the US, while the cultivar 'Bintji', introduced in 1910, remains a leading potato cultivar in the Netherlands.

In conclusion, modern-day crops have shown significant yield increases over the past century. It would be mistaken to suggest that the major contributor to this increase has simply been a direct result of plant breeding. Increases have rather resulted from a combination of plant breeding and improvements in crop husbandry. For example, the increased use of inorganic nitrogen fertilizer has greatly increased wheat (and other cereal) yield. However, this was allied with the introduction of semi-dwarf and dwarf wheat cultivars that allowed high nitrogen fertilizer application without detrimental crop lodging. Without the addition of nitrogen fertilizers, would the dwarf wheat cultivars have been beneficial? Probably not. However, would high nitrogen fertilizer application have been possible without the introduction of dwarf wheat cultivars? It is difficult to know. The overall increase achieved to date has resulted from both genetic and non-genetic changes in agriculture. In addition, it has been shown that significant, consistent genetic progress has been achieved not only under well managed conditions, but also under stressful conditions such as drought tolerance.

In the future the same is likely to be true: that the next leap in crop productivity will result from a marked change in agronomic practice, plus the introduction of plant types that can best utilize this husbandry change. What changes will these be? It is impossible to know with any certainty. Recent moves to reduced/no-tillage systems may be one option that could be considered, and that would require specific cultivars to maximize performance under these situations.

Similarly, advances in biotechnology may result in the development of crops with markedly different performances and adaptations to those available today. Introduction of these crop types may necessitate a major (or minor) change in crop husbandry to utilize the potential of these genetically modified crops.

Think questions

(1) Different crop species originated in different regions of the world. List the centres of origin of the following ten crop species: onion (*Allium* spp), alfalfa (*Medicago sativa*), rice (*Oryza sativa*), potato (*Solanum tuberosum*), soybean (*Glycine max*), sorghum (*Sorghum bicolor*), cotton (*Gossypium* spp.), sunflower (*Helianthus* spp.), wheat (*Triticum* spp.), and apple (*Malus* spp.).

(2) A combination of natural selection, and selection directed by plant breeders (early and modern), has influenced the crops we now grow. List five characteristics that mankind has selected which would not have been selected by a process of natural evolution.

(3) "The yield of many crops species has risen dramatically over the last 50 years. This has been the direct result of plant breeding during this period and hence the trend is likely to continue over the next 50 years." Briefly discuss this statement.

(4) "The place of origin of crops, their history and evolution are events from the past and therefore have no relevance to modern plant breeding." True or False? Discuss your answer.

(5) Many believe that civilization (of humans) started with the beginnings of agriculture. Basically there are two forms of agriculture: (1) rearing animals for meat, milk, etc., and (2) raising crops for human or animal feed. No one knows which form of agriculture evolved first (or maybe both types started together). Explain why (in your opinion) one form came before the other or both forms evolved at the same time.

(6) A combination of natural selection, and selection directed by plant breeders (early and modern) have influenced the crops we now grow. Have modern plant breeders improved the genetic fitness of our agricultural crop species, or have they simply selected plant types that are more suited to modern agricultural systems?

(7) A tremendous amount of plant diversity exists within Australia. Why, therefore, are there few Australian aboriginal farmers, and almost none

of today's world crop species had their centre of origin in the Australian continent?

(8) You are drifting your way through life when there is a crash and a tremendous flash of light, and from nowhere an alien spaceship lands. The alien, speaking perfect English, says "*I bring to you a gift: the Universe's most productive and perfect crop species*". Thereafter the alien gives you a bag of 200 seeds, returns to the spacecraft and whoosh, it is gone. Describe what you would do with the seeds and what information you would collect that would allow you to develop new cultivars from these seeds.