Plant Breeding

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***Abstract* - To respond to the increasing need to feed the world's population, standing at 7.1–7.2 billion in 2013 and predicted to reach over 9 billion by 2050, as well as an ever-greater demand for a balanced and healthy diet, there is a continuing need to produce improved new cultivated varieties of crop plants. Land available for crop production is limited and has stayed at 660 million hectares for the past 50 years. Much of the world's best soils are already in use and others are protected, for example, for environmental concerns. The demand for food brings marginal lands into play for which stress-tolerant crops need to be developed. Climate variation is yet another challenge breeders have to respond to. In short, more food, fibre, fuel and forage need to be produced per unit of land, and time is of the essence. The strategies used to meet these demands are increasingly based on our knowledge of relevant science, particularly genetics and reproductive biology. Success is gained by a multidisciplinary understanding and the deployment of relevant science and technology. Plant breeders must have access to genetic variation in crop species. Plant breeders must be equipped with the tools to respond quickly to new demands by developing accelerated breeding techniques and the ability to screen for traits of interest rapidly among progeny. Yield and yield stability remain the top priorities for breeders. Increasing production of plant products is essential for food, feed and fibre for the increasing World population. Breeders must be visionary in planning for requirements in the future, at least 7–20 years ahead, as this is the timescale from initiating the breeding Programme to release cultivars.**

INTRODUCTION

In plant breeding the aim is to produce new, improved varieties/cultivars and so we need, as a first requirement of any breeding Programme, to release or produce genetic variation in the characters (or traits) in which we are interested. Once such variation is released it is necessary to identify and then select the desired types – those that have a better expression of a particular character or combination of characters. Once identified the selected types need to be stabilized and multiplied for use and exploitation (Figure 1). Written in these terms it appears a relatively simple process, and in many ways the philosophy underlying crop improvement is simple. Although the practical reality is more complex it is possible to identify these three parts and see a framework in which to understand what is being done and what alternatives might exist. Each of these elements is tailored to be appropriate to the particular type of crop, or species, or even the likes and requirements of an individual breeder.

HISTORY

Plant breeding is an ancient activity, dating to the very beginnings of agriculture. Probably soon after the earliest domestications of cereal grains, humans began to recognize degrees of excellence among the plants in their fields and saved seed from the best for planting new crops. Such tentative selective methods were the forerunners of early plant-breeding procedures.

The results of early plant-breeding procedures were conspicuous. Most present-day varieties are so modified from their wild progenitors that they are unable to survive in nature. Indeed, in some cases, the cultivated forms are so strikingly different from existing wild relatives that it is difficult even to identify their ancestors. These remarkable transformations were accomplished by early plant breeders in a very short time from an evolutionary point of view, and the rate of change was probably greater than for any other evolutionary event.

In the mid-1800s Gregor Mendel outlined the principles of heredity using pea plants and thus provided the necessary framework for scientific plant breeding. As the laws of genetic inheritance were further delineated in the early 20th century, a beginning was made toward applying them to the improvement of plants. One of the major facts that emerged during the short history of scientific breeding is that an enormous wealth of genetic variability exists in the plants of the world and that only a start has been made in tapping its potential.

The plant breeder usually has in mind an ideal plant that combines a maximum number of desirable characteristics. These characteristics may include resistance to diseases and insects; tolerance to heat, soil salinity or frost; appropriate size, shape, and time to maturity; and many other general and specific traits that contribute to improved adaptation to the environment, ease in growing and handling, greater yield, and better quality. The breeder of horticultural plants must also consider aesthetic appeal. Thus, the breeder can rarely focus attention on any one characteristic but must take into account the manifold traits that make the plant more useful in fulfilling the purpose for which it is grown. Plant breeding is an important tool in promoting global food security, and many staple crops have been bred to better withstand extreme weather conditions associated with global warming, such as drought or heat waves.

INCREASE OF YIELD

One of the aims of virtually every breeding project is to increase yield. This can often be brought about by selecting obvious morphological variants. One example is the selection of dwarf, early maturing varieties of rice. These dwarf varieties are sturdy and give a greater yield of grain. Furthermore, their early maturity frees the land quickly, often allowing an additional planting of rice or other crop the same year.

Another way of increasing yield is to develop varieties resistant to diseases and insects. In many cases the development of resistant varieties has been the only practical method of pest control. Perhaps the most important feature of resistant varieties is the stabilizing effect they have on production and hence on steady food supplies. Varieties tolerant to drought, heat, or cold provide the same benefit.

MODIFICATIONS OF RANGE AND CONSTITUTION

Another common goal of plant breeding is to extend the area of production of a crop species. A good example is the modification of grain sorghum since its introduction to the United States in the 1750s. Of tropical origin, grain sorghum was largely confined to the southern Plains area and the Southwest, but earlier-maturing varieties were developed, and grain sorghum is now an important crop as far north as North Dakota.

Development of crop varieties suitable for mechanized agriculture has become a major goal of plant breeding in recent years. Uniformity of plant characters is very important in mechanized agriculture because field operations are much easier when the individuals of a variety are similar in time of germination, growth rate, size of fruit, and so on. Uniformity in maturity is, of course, essential when crops such as tomatoes and peas are harvested mechanically.

The nutritional quality of plants can be greatly improved by breeding. For example, it is possible to breed varieties of corn (maize) much higher in lysine than previously existing varieties. Breeding high-lysine maize varieties for those areas of the world where maize is the major source of this nutritionally essential amino acid has become a major goal in plant breeding. This “biofortification” of food crops, a term which also includes genetic modification, has been shown to improve nutrition and is especially useful in developing areas where nutritional deficiencies are common and medical infrastructure may be lacking.

In breeding ornamental plants, attention is paid to such factors as longer blooming periods, improved keeping qualities of flowers, general thriftiness, and other features that contribute to usefulness and aesthetic appeal. Novelty itself is often a virtue in ornamentals, and the spectacular, even the bizarre, is often sought.

EVALUATION OF PLANTS

The appraisal of the value of plants so that the breeder can decide which individuals should be discarded and which allowed to produce the next generation is a much more difficult task with some traits than with others.

QUALITATIVE CHARACTERS

The easiest characters, or traits, to deal with are those involving discontinuous, or qualitative, differences that are governed by one or a few major genes. Many such inherited differences exist, and they frequently have profound effects on plant value and utilization. Examples are starchy versus sugary kernels (characteristic of field and sweet corn, respectively) and determinant versus indeterminant habit of growth in green beans (determinant varieties are adapted to mechanical harvesting). Such differences can be seen easily and evaluated quickly, and the expression of the traits remains the same regardless of the environment in which the plant grows. Traits of this type are termed highly heritable.

QUANTITATIVE CHARACTERS

In other cases, however, plant traits grade gradually from one extreme to another in a continuous series, and classification into discrete classes is not possible. Such variability is termed quantitative. Many traits of economic importance are of this type, e.g., height, cold and drought tolerance, time to maturity, and, in particular, yield. These traits are governed by many genes, each having a small effect. Although the distinction between the two types of traits is not absolute, it is nevertheless convenient to designate qualitative characters as those involving discrete differences and quantitative characters as those involving a graded series.

CLASSICAL BREEDING

Release/production of variation

Conventionally this is achieved through sexual crossing, particularly of cultivated lines, in other words following Mendel's principles. Two parents who have expression of the desirable characters between them are intercrossed and the subsequent generations examined for plants with the desired characters in new combinations, i.e. we look for recombinants. This process therefore basically relies on the segregation of alleles at all the relevant genetic loci, during the normal process of meiosis (the reduction divisions that are undertaken to form the egg and pollen cells that fuse at fertilization). At fertilization there is a random fusion of gametes (pollen from the one plant and egg from the other) to give the embryo which develops into the seed. So, by the natural process of sexual reproduction, but between plants that the breeder has deliberately chosen, we get offspring that contain novel combinations of the alleles that were originally dispersed between the two parents. Clearly the choice of parents is critical. Sources of variation. The breeder generally uses the natural variation that already exists within the species. For virtually all char-acters we only need to look or measure any character to observe variation in their expression, and often this reflects not just variation produced by differences in the environment in which the plant happens to be growing, but also genetic variation – variation that is heritable. This naturally occurring source of heritable variation accounts for most of the responses that have been made in plant breeding. However, reliance on this one source of variation does limit the potential for long-term progress, particularly in relation to improving specific characters. So, the use of intra specific variation of existing crop cultivars is supplemented by one of the following. Wild, ancestral relatives of the crop itself: these may or may not still be able to cross sexually with the crop species and may be indigenous in another country. Inducing the variation that is required: the genetic variation that we see around us actually comes from the occasional and rare mistakes that occur in the otherwise faithful replication of the DNA in all organisms. These occasional mistakes are called mutation.

Breeding objectives and important traits

The general objectives of virtually all breeders of crop plants are to increase the usable yield, increase its stability, ensure the quality and nutritive value, and produce types that suit the particular growing conditions and farmingneeds.1. Usable yield. This means that it is not crude yield that is important but the part that can actually be used, eaten, processed, etc. This therefore brings in factors such as the storage life, waste produced and consumer acceptance. Also, it means that the use that the crop will be put to is of major importance, i.e. for direct human consumption, animal foodstuff, processing etc., and this must be considered at the outset of the breedingprogramme.2. Stability of yield. The fact that some lines/cultivars/varieties do very well in some years or under some particular conditions may be useful but can lead to disaster when they fail because of changes in the growing conditions, a poor year for rain, no fertilizer available, to wet a period at harvest etc. Thus, breeding for resistance/tolerance to all biotic and abiotic stresses is a major aim.3. Quality of the product. This includes nutritional quality and taste and is related to the awareness of usable yield but is concerned with the nutritive value, calorific value, protein content, fat level, vitamin concentration etc.4. Environmental impact. Agriculture affects any area where it is practiced and so generates considerable debate in many parts of the world – and quite rightly so. There are many aspects to this issue and all affect the plant breeder's aims and objectives. There are therefore much clearer calls for more ecologically sympathetic methods to achieve these aims. The production of varieties with disease and pest resistance is an obvious route to follow. Taking this further, if, for example, low-nitrogen input is required then clearly specific varieties will need to be produced that grow best under these conditions.5. Better adapted. The need to produce varieties that have been selected to grow under prevailing conditions is clear but easily overlooked. This may be the climate of a particular geographical location, the narrow conditions of a local area, the type of agricultural practices used, the needs of the farmer/village/countryetc.6. Prediction. Every breeder knows that it takes a number of years from starting to breed a cultivar until its release to the grower (often 10 years or more). This means that a breeder requires an ability to forecast the future, i.e. be a crystal ball gazer. So, for example, a breeder might need to assess/guess:(i) What will growers be requiring in the future?(ii) What will happen in terms of the emphasis for growers, e.g. what subsidies will there be and what will the political situation be in the future?(iii) How will climate change have affected growing patterns?(iv) How will farming systems have changed?(v) What will be the spectrum of diseases and pests?(vi) What will the end-users require in the future?

PLANT TRANSFORMATION

The stable introduction of specific genes into plants represents one of the most significant developments affecting the production of crop species in a continuum of advances in agricultural technology. The progress in this area has depended largely on the tissue culture systems having been developed which, at least, initially, provide an amenable vehicle for the transformation induction. The term transformation comes from that used for a much longer period, bacterial transformation, in which DNA has been successfully transferred from one isolate to another or another species of bacteria and integrated into the genome.

It was shown that the stably transformed bacteria then expressed the new genes and displayed appropriately altered phenotypes. In eukaryotes, transformation has a further complicating dimension, at least in many plants' breeding contexts. The transforming DNA must not only be integrated into a chromosome, but it must also be a chromosome of a cell, or cells, that will develop into the germline. Otherwise, the transformation will not be passed on to the next generation. Using plant transformation techniques, it is possible to transfer single genes (i.e., simply inherited traits) into plants, to have such transgenes expressed and for them to function successfully. Theoretically at least, specific genes can be transformed from any source into developed cultivars or advanced breeding lines in a single step. Plant transformation, therefore, would appear to allow plant breeders to bypass barriers that limit sexual gene transfer and to exchange genes (and traits) from unrelated species between which sexual hybridization is not possible. These recombinant DNA techniques, apparently, allow breeders to transfer genes between completely unrelated organisms. For example, bacterial genes can be transferred and expressed in plants. This appears to break the barrier that sexual reproduction generally imposes. However, as we learn more about the DNA, and hence the genes involved, the perspective of the picture changes somewhat, with increasing direct evidence of the presence in different species of the same basic gene, or clear variants of it, and demonstrations of the greater conservation of genetic material (synteny) during evolution than we expected. Also, we are being reminded of the existence of parallel natural processes for much of what we regard as novel. For example, bacteria, viruses and phages already have successfully evolved mechanisms to transfer genes just in the way we regard as being so alien! But clearly, the new techniques are allowing modern plant breeders to create new variability beyond that existing in the currently available germplasm on a different scale and in a different time frame from that which was previously possible.

Although plant transformation has added (some say dramatically) to the tools available to the breeder for genetic manipulation, it does have limitations. Some of the limitations will reduce with increased development of methodologies, others are inherent to the basic approach. At present recombinant DNA techniques can generally only transfer rather limited lengths of DNA and so tend to be restricted to the transfer of single genes. This means that they are very effective where the trait can be substantially affected by a, or a few, gene(s) of large effect.

Another restriction that is imposed currently is that the techniques are only readily applied to genes that have been identified and cloned. The number of such desirable genes is still modest but increasing rapidly.

Some applications of genetic engineering to plant breeding

Already there is a growing list of crop species that have proved successful hosts for transformation including alfalfa, apple, carrot, cauliflower, celery, cotton, cucumber, flax, horseradish, lettuce, maize, potato, rapeseed, rice, rye, sugar beet, soybean, sunflower, tomato, tobacco and walnut. Initial cultivar development using recombinant DNA techniques has focused on modifying or enhancing traits that relate directly to the traditional role of farming. These have included the control of insects, weeds and plant diseases.

The first genetically engineered crops have now been released into large-scale agriculture (including maize, tomato, canola, squash, potato, soybean, and cotton) and other species are already in the pipeline. More recently work has focused on altering end-use quality (including oil composition, starch, vitamin level and even vaccines).

CAUTIONS AND RELATED ISSUES

There have been a number of concerns that have arisen over the past few years as the application of plant transformation technology has expanded and particularly as new transgenic crops have been released into commercial cultivation. Plant breeders need to be aware of the concerns as well as the regulations that apply to plants derived using recombinant DNA. As well as the general social and environmental concerns the breeder must check that the techniques being used are the most effective for what is to be achieved and not simply assume that high tech means most efficient!

MOLECULAR MARKERS IN PLANT BREEDING

Although plant breeders have practiced their art for many centuries, genetics is a subject that really only came of age in the twentieth century with the rediscovery of Mendel's work. Since then, research in genetics has covered many aspects of the inheritance of qualitative and quantitative.

CONCLUSION

There are many classical and modern breeding techniques that can be utilized for crop improvement in agriculture despite the ban on genetically modified organisms. For instance, controlled crosses between. individuals allow desirable genetic variation to be recombined and transferred to seed progeny via natural processes. Marker assisted selection can also be employed as a diagnostics tool to facilitate selection of progeny who possess the desired trait(s), greatly speeding up the breeding process. This technique has proven particularly useful for the introgression of resistance genes into new backgrounds, as well as the efficient selection of many resistance genes pyramided into a single individual. Unfortunately, molecular markers are not currently available for many important traits, especially complex ones controlled by many genes.

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